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LUNAR DRILLING IMPLEMENT

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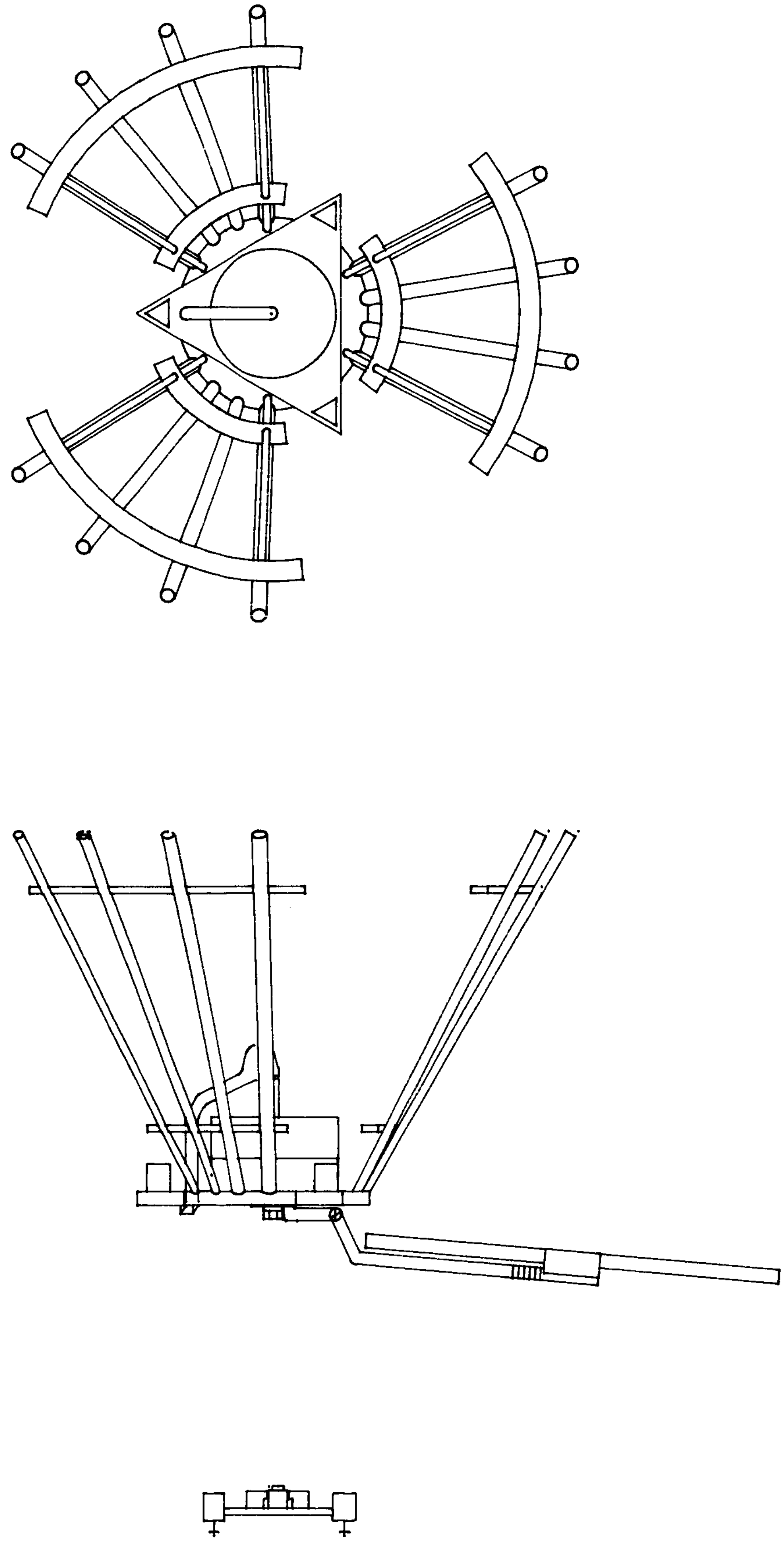

ABSTRACT

By the year 2000, a serious effort will be underway to expand exploration of the lunar surface. This report is concerned with the development of a lunar drilling device that can make a hole 30 meters in depth with a diameter large enough to accommodate a 100 millimeter instrument package. The drilling device is an implement that will attach to a three-legged arthropod platform, which will transport the device to each drilling site. Once at the drilling site the lunar drilling implement will operate in conjunction with this mobile platform. Everything that is needed for operation of the drilling implement will be contained inside the device, thus allowing remote operation of the lunar drilling implement.

This design incorporates several unique features worthy of mention: the use of heat pipes to cool the drill bit, an electromagnetically activated solenoid to remove the cuttings made by the drill, and a curvilinear synchronous motor to provide the drilling action. All these features were found to give a significant advantage over previous lunar drill designs.

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SECTION 1 INTRODUCTION

1.1 PROBLEM STATEMENT

A lunar drilling implement (LDI) is to be designed that is capable of making a hole in the lunar surface which is up to 30 meters deep and able to accommodate a 100 millimeter diameter probe. The implement will attach to and operate from an arthropod walker through a mechanical interface. The orientation or placement of the hole will only be limited by the arthropod's ability to negotiate the lunar landscape and to provide the necessary motion for the implement to operate without interference by either the landscape or the arthropod. The device is to be fully automated, remotely controlled, and self-powered. The implement should be designed to provide safe, fast, and efficient operation while exposed to the hazards of the lunar environment. Weight should be minimized to reduce shipping costs, but without sacrificing reliability or performance.

1.2 DESIGN OVERVIEW

The LDI is a fully automatic, remotely controlled, self powered apparatus capable of making a 120mm diameter hole up to 30m deep in the moon's crust. It is intended to be attached to a three legged lunar arthropod and operated in conjunction with the arthropod. Therefore, the type of terrain in which the LDI can operate, and the orientation of the hole, will only be limited by the movement capabilities of this mobile platform. The construction of the implement is based on a triangular aluminum plate which will attach to the bottom of the arthropod. On the top of this plate and inside the body of the walker will be the motor, batteries, and associated controls for the LDI. Extending from each of the sides of this plate and running parallel to the outsides of the arthropod's body are three trays which will hold the drill string elements. The implement is constructed in such a manner that it will not interfere with any of the motions of the arthropod while it is walking out to the drill site.

When not in use, the implement will sit in a free standing cradle. To deploy the implement, the arthropod will squat down and attach to three hook-up points. The interface between the two machines will be mechanical only; each system being controlled separately but relying on communication from the other.

Upon arrival at the drill site, the arthropod will squat down over the desired location of the hole and lower an auxiliary drilling platform (ADP). The ADP will facilitate the assembly and disassembly of the drill string by holding and stabilizing the drill rods in the hole. The drill string elements will be moved from the storage trays to the drill chuck by a manipulator arm attached to a rotating turntable.

The cutting will be accomplished with a diamond drill bit cooled by heat pipes. The apparatus will be powered by batteries, and a curvilinear synchronous motor will perform the drilling action. As the cuttings are made, they will be channeled to an external auger flight which will lift them up to openings in the side of the drill string, through which they will fall into a collection hold. Periodic activation of the solenoid will result in the chips being ejected up through the center of the hollow drill string. This passageway will extend through the inside of the implement to up above the body of the walker where the cuttings will hit a directional deflector and be doposited onto the lunar surface. Power for the solenoid will be supplied via electrical conductors embedded into the composite matrix of the drill string elements. A complete illustration of the overall design can be seen in Appendix A, Drawing 1.

1.3 OPERATION SEQUENCE

1. The implement will be stored in a free standing cradle when not in use.

2. The arthropod will move over the implement, squat down, and attach to 3 mechanical hook-up points. The arthropod will provide all necessary latching motions.

3. The arthropod will walk, carrying the implement, to the drill site.

4. The walker will squat and place the Auxiliary Drilling Platform (ADP) over the point where the hole will be drilled.

5. The lead drill string element will already be held by the manipulator arm.

6. The manipulator arm will swing down, and place the lead drill string element into the chuck. The arm will then swing back to avoid interfering with the drilling motion.

7. Once drilling begins the arthropod supplies the thrust and vertical motion.

8. While drilling, the cuttings will be ejected by an electromagnetic solenoid through the center of the hollow drill string. The chips will hit a directional deflector as they exit the top of the implement.

9. When the limit of advance of the drilling is reached, the motor will be stopped and aligned so that the ADP can grab the top end of the lead drill string element.

10. The collet like chuck will then be released by raising the slip ring until it contacts the mating surface of the turntable. This will allow the motor to rotate the arm to the next storage position and grasp a second drill string element. The arm will then swing down through a 150 degree angle and orient the element so that it is parallel to the axis of the CSM. Then in a combined linear-rotary motion the element will be rotated and pulled up into the chuck.

11. The arm will again swing up out of the way, and the walker will squat and connect this next element to the lead element held by the ADP.

12. The ADP will then release the lead element and drilling will continue with drill string vibration and rotary speed being monitored.

13. When the limit of advance of drilling is again reached, the motor will stop and align the drill string element so that the ADP can grab the drill string. The chuck will then release the drill string and another element will be added.

14. This process will be repeated until the specified depth is reached.

15. To disassemble the drill string, the arthropod will raise itself and the motor will align the drill string so that the connection between the top two elements is oriented such that the ADP can grab the drill string and release the connecting latches.

16. The walker will then stand and the arm will grab the element held by the chuck and return it to its proper position in the storage tray.

17. The walker will then squat and reattach to the remainder of the drill string. The ADP will disengage, and the arthropod will stand back up and perform the same alignment procedure. The ADP will be reactivated, and the arm will restore the next element as before.

18. This process will continue until all elements have been returned to their storage positions.

19. The arthropod will then squat and pick up the ADP and leave the drilling site.

SECTION 2 COMPONENT DESCRIPTIONS

2.1 BODY AND STRUCTURE

The body of the implement will have as its foundation a triangular frame structure, made of an aluminum alloy, which will attach to the walker through three mechanical interface points. Extending from each of the sides of this plate will be three conical shaped storage trays that will hold the drill string elements (see drawing # 3). These will also be constructed of an aluminum alloy and will be attached to the base plate. Earlier ideas called for an external drill string tray that would be carried to the drill site underneath the base of the walker. Due to possible interference with the arthropod's legs while walking this idea was decided against.

The main motor and other components will be attached to a frame extending from the top of the drilling base to inside the body of the walker. The batteries will be supported on the inside frame of the walker. Inside the base plate will be a turntable, running on sealed bearings, to which the manipulator arm will be attached (see drawing # 2). The turntable will be rotated using the drilling mechanism with the drill chuck in the fully open position (see drawing #2).

2.2 DRILL STRING COMPONENTS

The term "drill string" refers to the assembly of drill rods and the drill bit. The drill string for the Lunar Drilling Implement (LDI) consists of two primary elements: the drill bit and drill rods.

2.2.1 DRILL BIT

As previously mentioned, the two major problems involved in a "dry drilling" process are cutting removal and bit temperature control. The drill bit design for the LDI incorporates features to address these problems.

Detailed drawings of the bit are shown in drawing numbers 4 and 5. The cutting surfaces that are in actual contact with the rock are oriented such that the cuttings are swept toward the outer diameter of the drill bit as the bit rotates. This orientation will facilitate the prompt removal of the cuttings by a series of auger flights on the outside of the drill bit.

The drill bit will be 3 meters long, although only a small portion of the lower end is involved in the actual rock cutting operation. The remaining length of the bit is used for the cutting removal system and the bit cooling system.

The lower length of the drill bit contains a triple threaded auger flight. As the drill is rotated, the auger flight will lift the cuttings away from the cutting surface of the bit. At the end of the each auger flight, there is a hole which will permit the cuttings to fall inside of the drill bit and into the cuttings ejector system.

It is estimated that prompt removal of the cuttings dissipates approximately 80% of the heat generated by the drill bit. To remove even more heat from the bit, a series of heat pipes have been incorporated into the bit design for the LDI. A heat pipe consists of a sealed tube-like container that is internally lined with a wick and filled with a fluid. Heat is transferred by the cyclic evaporation of the fluid at the heat source and the condensation of the fluid at the heat sink. The wick material creates a capillary effect which draws the condensed fluid back to the evaporator section of the heat pipe. The overall thermal conductivity of a heat pipe is hundreds of times greater than the conductivity of the best solid conductors. Furthermore, heat pipes have no moving parts and do not require gravity for operation. The LDI drill bit will use a liquid mercury heat pipe with a steel mesh wick. The selection of this type of heat pipe was based on the potentially high service temperatures of the drill bit. Theoretical calculations for the heat pipe design can be found in Appendix B. Nine heat pipes will be located between the outer diameter and inner diameter of the drill bit. Holes drilled through the annular cross section of the bit will serve as the "tube" structure for the heat pipe. The heat pipes will be sealed by welding the end cover of the drill bit to the drill bit body with an electron beam weld. To maximize the effective heat transfer, the evaporator section of each heat pipe will be located in close proximity to the cutting elements in the drill bit matrix. The heat drawn to the top of the drill bit will be dissipated through radiative heat transfer and conduction with the drill string.

A variety of different cutting diamonds were studied for use on the LDI drill bit. A synthetic diamond, produced by the General Electric Company, Specialty Materials Department was selected over conventional mined drilling diamonds. The drilling diamond, known by the trade name GEOSET, is a triangular shaped diamond of approximately 3.0 carats. It has a number of advantages over conventional drilling diamonds. First, it is a polycrystalline diamond with no inherently weak cleavage planes. This means that the orientation of the cutting elements is not critical. Secondly, unlike mined diamonds which tend to polish smooth with wear, GEOSET diamonds actually sharpen with wear. Lastly, it should be noted that conventional methods can be used to bond GEOSET drilling diamonds to drill matrix materials and to recover worn diamonds from used drill bits.

The drill matrix material for the LDI drill bit will be carbide steel. This type of matrix is quite common in today's earth drilling operations.

2.2.2 DRILL RODS

In order for the LDI to achieve its required maximum drilling depth, it will carry ten 3 meter drill rods. Drawings of the typical drill rod may be found in drawing numbers 6 through 8.

The drill rods will be made of a fiber composite material. This selection was based on the excellent strength to weight ratio of composites and their resistance to cold welding in a vacuum environment. Several combinations of graphite/epoxy and graphite/polymide composites were evaluated. It was determined that an addition type of polymide matrix would be desirable due its high working temperatures and elastic modulus, and low void content. The graphite/polymide composite also had the desirable qualities of high thermal conductivity and an extremely small coefficient of thermal expansion. Tests conducted at temperatures of -250 to 350 F on the graphite/polymide composite Celion 6000 / PMR-15 have shown that ultimate strength and elastic modulus are not strong functions of temperature. The optional addition of Kevlar fibers to the inner and outer layers of the drill rods would greatly enhance the impact resistance of the composite drill rods.

Lastly, to avoid possible radiation embrittlement, the drill rods will be protected with a white paint similar to that used on past Apollo missions.

The basic cross sectional shape of the drill rods is an octagon. This geometry was chosen to simplify the drill chucking operation required to hold the drill rod. A hole that runs through the length of each drill rod provides a passage to remove rock cuttings with the cuttings ejector system.

Each drill rod has a male and female connecting end. The female connecting joint consists of four spring finger latches and an octagonal shaped socket. The assembly of the male connector into the female socket creates a socket joint that will carry the torque transmitted to the drill rod. The assembly of the finger latches into the corresponding latch receptacles in the male joint create a snap together fitting that will carry tensile loads encountered when the drill string is being withdrawn from the hole.

The finger latches are embedded in the composite material of the drill rod. The leading edge of the latches is tapered so that the latches deflect when they are inserted into the latch receptacles in the male joint. Once the finger latches pass over a small latching edge inside of the latch receptacles, they return to their natural, undeflected position. The finger latches also have a small amount of curvature in them to permit some longitudinal spring deflection in the event that one latch might be shorter than the other three. This will avoid the condition of one latch bearing the entire tensile load. Because of its relatively consistent properties over a wide range of temperatures, stainless steel was chosen for the latch material.

Each latch receptacle on the male end of the drill rod has a small hole through the outside of the drill rod surface. During disassembly operations, tools on the Auxiliary Drilling Platform are inserted into these holes and deflect the finger latches past the latching edge inside of the receptacle. With the latches deflected, the two drill rods can then be disassembled by simply pulling them apart.

As an additional feature, the finger latches provide the electrical connections needed to operate the cutting ejection system (See Drawing # 9). A portion of the latch is covered with a thin layer of an electrical conductor that is placed over a layer of insulating material. These two layers are attached to the latches with an epoxy suitable for the lunar environment. A similar arrangement exists in each of the latch receptacles. Assembly of the drill rods brings the two conducting surfaces into contact. The contact surfaces on each finger latch are connected via an insulated wire embedded in the composite drill rod to the corresponding latch receptacle on the opposite end of the drill rod. By providing electrical connections for all four pairs of latches and latch receptacles, the radial orientation requirements for connecting two drill rods together are greatly simplified.

2.3 CURVILINEAR SYNCHRONOUS MOTOR

By definition, an electrical drive is the combination of an electric motor and the entire control equipment selected to meet the load requirements. In the case of the Lunar Drilling Implement, the load requirements are (8 HP) at a speed of one thousand revolutions per minute (RPM). A variable speed drive is designed such that the speed can varied over a set range as a function of torque. The components making up such a variable speed drive include the electrical machine, the power source, the power converter, the control equipment and the mechanical load.

For use with LDI, the electrical machine was chosen to be a Curvilinear Synchronous Motor. The Curvilinear Synchronous Motor (CSM) resembles a Linear Synchronous Motor (LSM). It can provide rotary motion because it is curvilinear, but it has the same winding configurations as those of an LSM. This design gives advantages including a relatively flat torque speed profile, low maintenance requirements, high reliability, and an efficiency approximately 300-400% greater than other motor drives. These are obtained by the elimination of gears, pulleys, belts, and permanent magnet DC motors which greatly improve the reliability and durability of the system.

The CSM itself consists of two essential elements, a stator and a rotor. These two elements are disks which are placed in parallel planes with minimal spacing between them. The rotor is simply a set of magnets radially oriented alternating north-south in the peripheral direction around the disk. The stator is made up of a three phase winding embedded in an iron powder substrate. By altering a three phase excitation in the stator, control and torque generation are achieved.

The diameter of the CSM needed for the lunar drill is eighty eight centimeters. Iron boron magnets measuring fifteen by two by two centimeters are used in the manner described earlier. With proper spacing between these two disks, the speed requirement of 1000 RPM can easily be reached without excessive back EMF.

The power source needed for the variable speed drive is discussed in section 2.7.

The power converter required is actually an inverter with a conversion function of fixed potential DC to variable potential and variable frequency AC. A three phase MOSFET inverter is capable of producing the required sinusoidal current waveforms.

The AC synchronous machine is a complex, nonlinear, multivariable control plant. A DC motor has a simple control structure but a complex mechanical design. On the contrary, the AC synchronous motor has a simple mechanical design with a very complex control structure. State variable feedback is required to "synchronize" electrical frequency to mechanical speed in order to operate the variable speed AC synchronous motor. Angular position feedback is necessary to extend the electrical frequency range to DC , that is, start-up from zero velocity. This is implemented most inexpensively with a hall effect transducer. Continuous operation is accomplished by effectively creating a current source which tracks mechanical speed and phase.

The mechanical load of the system is the force required to rotate the drill string at the desired RPM. The CSM will also be used to rotate the manipulator arm in order to correctly position it for drill string assembly and disassembly. This load, though, is minimal when compared to that needed for drill string rotation.

This system is very reliable and efficient, relatively small, and has a mass of only (150 lbf) without the power supply. See drawing # 10 in Appendix A for an illustration of the CSM.

2.4 MANIPULATOR ARM AND CHUCK MECHANISM

The drill string elements will be moved between their positions in the storage trays and the drill chuck by a manipulator arm. Attached to a rotary turntable driven by the curvilinear synchronous motor (CSM), the arm will index to one of twelve storage stations, grasp a drill string element and swing it down until it is oriented parallel to the axis of the CSM. Next, in a combined linear and rotary motion, the element will be positioned into the chuck. The clamping mechanism will then release and the arm will swing up and align itself parallel with one of the storage trays so that it will not interfere with drilling operations.

Drawing number #11 in Appendix A shows an overall view of this arm. It will be constructed primarily of tubular aluminum with iron. Composite materials will be used where sliding motions require different material characteristics. A DC servo-motor and electromagnetic solenoid actuators will provide all the necessary motions.

At its pivot point connection to the turntable, the arm will have a 140mm diameter DC servo-motor that will be used to swing it up and down through its 150 degree range of motion. A momentary maximum torque of 46mN will be required to move the arm while it is positioning a drill string element. At the end of the arm will be a clamping mechanism used to hold the drill string elements. The two composite gripping surfaces are contoured to rest snugly against the six sides of the octagonally shaped elements. The clamps will be activated by a double sided, spring return, extension solenoid and will be mounted on aluminum pin joints. This mechanism will be contained within a rectangular aluminum housing.

This housing is connected to the iron plunger of a linear-rotary solenoid. This actuator will enable the arm to rotate the drill string element into alignment with the axis of the CSM and then pull it vertically into the chuck. The device is similar to a linear solenoid except that a pin riding in a groove on the plunger provides the rotary motion. By gradually increasing the current in the coils and having an appropriately selected spring rate, a smooth, controlled motion of the plunger can be achieved. The solenoid will have a 200mm stroke length. The various sliding surfaces involved in this mechanism will be protected from dust and other contaminants by a bellows type cover.

The chucking action will be accomplished using an arrangement similar to a collet. This mechanism is mounted to the end of the tubular aluminum shaft extending from the rotor of the CSM and is pictured in drawing #12. The eight rectangular shaped, composite clamping surfaces or "fingers" are mounted on spring loaded pin joints and will hold the drill string element by means of friction. These "fingers" will close around a drill string element by the vertical motion of the slip ring depicted in drawing number #13. This iron slip ring will be solenoid actuated and slide along grooves on the outside of the shaft extending from the CSM.

The entire arm assembly will be attached to a rotary turntable which is pictured in drawing number #14. This will consist of an aluminum disk mounted on sealed bearings embedded into the triangular base plate (see drawing #15). The turntable will be driven by the CSM. This will be accomplished by raising the slip ring used to close the chuck and causing it to come into contact with a mating surface on the turntable and thus drive it by friction. The angular positioning accuracy of the CSM is dependent upon its number of poles. By having 36 poles, the CSM is capable of accurately positioning the turntable, and thus the manipulator arm, to within less than 1 degree of the twelve drill string storage stations.

Because of the arrangement of the drill string elements, the turntable need not execute a full rotation to service each rack. Therefore, direct wiring can be used, eliminating the need for a brush-commutator type arrangement. Also, the friction associated with the bearing seals of the turntable is actually desired because it will serve as a brake to keep the turntable from drifting out of position when the slip ring is no longer in contact.

2.5 AUXILIARY DRILLING PLATFORM

The primary function of the Auxiliary Drilling Platform (ADP) is to hold and locate the drill string during assembly and disassembly of the drill string components. The ADP is shown in drawing number 16. The ADP features four clamping tools located around a hole to accommodate the drill string. Each clamping tool has an extension on it which fits into the finger latch receptacle holes on the male end of each drill rod. Inserting the extension into the finger latch receptacle hole causes the finger latches to deflect and permits adjacent drill string components to be pulled apart. The clamping tools are moved by electric linear actuators.

Since the actual "on time" of the ADP will be considerably less than the time of the total drilling process, the ADP should have relatively small data processing and power consumption requirements. To accommodate these requirements, the ADP will carry its own onboard power supply and microprocessor.

Because the orientation of the ADP to the drill string is critical, it will be necessary for the ADP to level itself with respect to the LDI when drilling operations are conducted on uneven terrain. The ADP will contain two leveling sensors to assist in this task. The Singer Company, Kearfott Division currently manufacturers a magnetically damped leveling sensor that may be suitable for use in the lunar environment. The leveling sensor consists of a pendulum mass on a rotor shaft. As the mass tends to seek the center of gravity, the rotor turns and induces an electrical signal in the stator. This signal is proportional to the angular orientation of the ADP. This signal will be analyzed by the onboard microprocessor which will in turn adjust the length of the ADP legs to achieve the level condition. The leg adjustment will be accomplished by electrical linear actuators located in each leg. To simplify the leveling process, the ADP is supported by only three legs which will define the plane of the ADP.

The ADP is designed to be carried underneath the LDI while the LDI / Lunar Arthropod are in transit. The ADP has a fixture which allows it to be held in place by the LDI drill chuck.

Since the ADP and LDI will be required to operate in unison, some type of communication channel will be required between the respective microprocessors. The only signals that will need to be transmitted will be the extend and retract commands for the clamping actuators. Since these are relatively simple communications, a radio transmitted signal should be feasible.

2.6 CUTTINGS EJECTOR SYSTEM

In order to keep the penetration of the lunar drill at a continuous rate, a chip removal system has to be implemented. Due to vacuum conditions on the moon, only a dry removal process can be used. After considering several ideas, it was concluded that an electromagnetic solenoid activated plunger, which would eject the cuttings through the to top of the arthropod, would be the most effective chip removal system.

The use of a solenoid to eject the cuttings is a simple procedure. As the drill bit penetrates the lunar soil, the cuttings will travel a short auger flight, fall inside the drill bit onto a circular plate and will be ejected out of the drill string through the solenoid activated plunger. In order to minimize the cuttings colliding with the inner wall of the drill string, the plate will be concave inward. This will permit the cuttings to collect in the center of the plunger (See Drawings # 17 & 18). No specific time is set for the "shoot rate" of the solenoid; however, the time is proportional to the penetration rate of the drill and will vary from 5 to 10 seconds.

Certain specifications have to be met in order for the solenoid to function efficiently. Size constraints are bounded by the drill string. A circular diameter slightly less than 70 millimeters is available for the plunger. This correlates to a circular cross sectional area of 0.0036 square meters. Solenoids are essentially short stroke devices limited to a maximum stroke of 0.1016 meters; therefore, this application will employ a stroke length of 0.1016 meters. Also, the number of coil turns required to generate the magnetic field must be determined. Calvin Miller, an electrical engineer for Bell Labs , studied the design and suggested 100 coil turns would be sufficient to generate the magnetic field.

After determining design specifications, force and DC current values need to be determined. An initial velocity of 14 meters per second is required to remove the cuttings from the drill string. All deterrents of cutting removal have been considered in calculating this value. The table in appendix B shows force as a function of several different mass values; and DC current as a function of the various force calculations. It is important to remember masses will vary with penetration rate; therefore, several force values need to be consider when evaluating the DC current.

Within the drill string a circular lip is needed between the plunger and the inner walls of the drill string. This lip will keep any dust particles from collecting beneath the plunger, as well as allow for the plunger and the inner drill string walls to come in contact with one another. A Teflon coating will be applied to the plunger to form this lip.

2.7 POWER SUPPLY

The LDI requires a power supply which is both compact and portable, yet will provide enough power to operate the drilling device continuously for several hours without recharging. In order to define a power system and determine the most appropriate power source, it is necessary to first determine the energy needs of the device.

The energy requirements for the lunar drilling implement include operation of an eight horsepower curvilinear synchronous motor, an electromagnetic solenoid, the control system, and processors and actuators, plus a 25% backup power supply. This means that the drilling implement will need at least 6 kilowatts of power in order to operate. Since the drill will be in continuous operation for at least 40 hours, the power supply must also be able to provide enough energy for this amount of time without recharging or refueling.

Another requirement to be considered is that the power supply be designed in such a way that it can be remote-controlled. Finally, because there is no significant atmosphere on the moon, the power supply must be able to operate under both high and low temperatures, and resist the effects of radiation. In order to meet all these requirements, three types of power supplies were considered: fuel cells, solar cells, and batteries.

Fuel cells are already widely used for many space applications. The most common type of fuel cell combines hydrogen and oxygen to produce electricity and water. This type of system has been widely used on several Apollo missions as well as on the Space Shuttle. Fuel cells provide the benefits of low weight, high power output, long life, and flexible modular components. Unfortunately, fuel cells require storage tanks to contain the oxygen and hydrogen necessary for the electricity production, plus a water tank is needed to store the waste water which is also produced. Due to the space limitations imposed on the LDI, this type of fuel source would not readily meet these space requirements.

Solar cells offer another option for power production. Although solar cells could easily provide the power necessary for the lunar drilling implement, the lack of available space on the arthropod again does not make solar cells a viable option.

Batteries are the final possible power source to be considered. Although they do not provide as much power as fuel cells, they do offer the special advantage of compactness. Also, there is no requirement for any additional storage containers separate from the batteries. Batteries can be operated by remote control, and will provide the necessary power to fulfill the lunar drilling implement's energy requirements.

It was decided that batteries would offer the best possible power source and would meet all the other necessary requirements. There are two types of batteries which could meet the specifications of the LDI: sealed nickel cadmium batteries and silver zinc secondary batteries. Using the product characteristics of Eagle-Picher Industries' silver zinc secondary cells, SZLR 320, it was found that 120 of these cells would provide 6 kilowatts of power (See Calculations, Appendix B). The total mass of this energy power source will be 329 kilograms. The total volume for this power package is 0.134 cubic meters. An illustration of the battery can be seen in drawing #19.

The present technology concerning energy sources is rapidly changing as new innovations are always being considered and evaluated. By the time the LDI is ready for production there will have been significant advances in the field of energy technology, and quite possibly a standardized power source for implements of this nature. For this reason it would be wise to continually update the nature of the power source to be used by the LDI.

2.8 CONTROLS

The primary control system on the LDI will involve monitoring and adjusting the rotational speed of the drill string. The control system is designed to maintain a drill speed in the range of 700 to 1000 revolutions per minute. These speeds have be judged to be the most efficient for diamond drilling operations. The speed will be continuously monitored and adjusted within the operating limits to produce maximum drilling efficiency.

The control system begins with an inputed drill speed from the central processing unit. At start up, this speed will be 700 RPM. A vibration transducer fixed to the drill chuck will continuously provide vibration telemetry to the central processing unit. The inputed drill speed will then be increased or decreased within the operating limits until an optimal speed, with minimal drill string vibration, is obtained. Should the vibration become excessive at all speeds within the desired range, the drilling process will be discontinued until the cause of the vibration can be identified and corrected. A tachometer attached to the drill motor will supply feedback to the control system in an effort to continuously decrease the error between the inputed drill speed and the actual drill speed. Drawing number #20 shows a diagram of this system.

As previously mentioned, the two primary transducers for this system are a tachometer and an accelerometer. Based on current vendor information, there appears to be a number of accelerometers available on the market today that would be acceptable for vibration measurement on the LDI. Gulton Servonic Division manufactures several types of servo accelerometers that have had wide use in military and space applications. Unfortunately, there were no current tachometers available that were suitable for use in the lunar environment. The majority of the tachometers had operating and storage temperatures that ranged from only -20 to 120 degrees Fahrenheit.

The central processor on board the Lunar Arthropod will supply additional information on the status of the drilling process. The primary information to be supplied is the current position of the Lunar Arthropod body above the lunar surface, and the rate at which this position is changing during the drilling process. This information corresponds to the instantaneous drill string position and the drilling penetration rate respectively. When the vertical position of the Lunar Arthropod reaches a critical value, the drill string assembly sequence will be initiated. If the drilling penetration rate falls below a critical value, then the drilling process will be discontinued. This would be an indication to check for excessive bit wear.

During the drill string assembly and disassembly process, it will be necessary for the drill chuck and drill string to have known and consistent radial orientations. These orientations should facilitate the grasping of the drill string components by the drill chuck, manipulator arm, and ADP clamps. As a result, it will be necessary to control and monitor the radial orientation of the drill chuck. To accomplish this, the CSM is designed with poles located in positions that correspond to the critical radial orientation positions of the drill chuck (i.e., stop positions for the manipulator arm or alignment positions for drill rod joints). A series of proximity switches located around the rotor shaft, with corresponding contacts on the rotor shaft, will supply radial orientation information to the microprocessor. The microprocessor will then index the motor until the correct radial orientation of the drill chuck is obtained for the current task at hand.

SECTION 3 DESIGN ESTIMATES

3.1 COST ESTIMATES

MATERIAL (COMPONENT)	COST/UNIT	AMOUNT	TOTAL COST
LEAD DRILL IMPLEMENT			
GEOSET Diamonds	$300 ea.	700	$210,000
Materials and Manufacturing			$50,000
Heat Pipes			$25,000
Cutting Ejection System			
Solenoid			$2500
Plunger			$300
Drill String (Celion 6000/PMR-15)	$60/lb	900 lb	$54,000
Coating(development & manufacturing)			$20,000
Drill String Manufacturing			$35,000
Triangular Frame Drilling Platform			$15,000
Curvilinear Synchronous Motor			$25,000
Motor Bearings	$5000 ea.	2	$10,000
Batteries	$100 ea.	120	$12,000
Drill String Trays			
Grip - Solenoid	$250 ea.	30	$7,500
Manufacturing	$3000 ea.	3	$9,000

Manipulator Arm			
Rotary Linear Electromagnetic Solenoid Actuator			$5,000
140mm Diameter DC Servo-Motor			$10,000
Manufacturing			$7,500
Turntable			$4,500
Enclosed Bearings - Turntable			$5,000
Drill Chuck			$3,000
Slip Ring			$300
Testing & Evaluation	$300/hr	1000hr	$300,000
Labor	$75/hr	2000hr	$150,000
TOTAL			**$960,600**

3.2 MASS ESTIMATES

DRILL STRING	913 lbm
LEAD DRILL STRING ELEMENT	80 lbm
TRIANGULAR FRAME DRILLING PLATFORM	550 lbm
CURVILINEAR SYNCHRONOUS MOTOR	200 lbm
POWER SUPPLY	723 lbm
TURNTABLE AND MANIPULATOR ARM	25 lbm
REMAINING COMPONENTS	250 lbm
TOTAL	**2741 lbm**

SECTION 4 FAILURE MODE ANALYSIS

In a system as complex as the LDI, there are obviously many potential failure modes. However, the following list presents the most serious failure modes which might be circumvented in future lunar drill designs.

1. Excessive Drill Bit Wear

This type of failure would typically be indicated by extremely low drill penetration rates or excessive vibration of the drill string. A variation of this type of failure would be excessive wear of cutting elements on only certain locations of the bit. Typically, drill bit wear is caused by extreme bit temperatures.

To accommodate for this type of failure, the LDI will carry a backup drill bit when it is used to drill holes in excess of 10 m in depth.

To reduce the potential of this type of failure, actual dry drilling in a lunar like environment should be conducted to determine the drilling parameters which would minimize this failure mode and further develop the dry drilling process. Furthermore, a drill design that would monitor the drill bit temperature would provide warning of impending bit failure and allow an opportunity to stop the drilling process and allow the bit to cool.

2. Mishandling of Drill String Elements

This failure mode involves the dropping of drill string components or any inability to correctly orient the drill string components. Due to the inflexibility of the current manipulator arm, assistance from some type of system external to the LDI (i.e., an astronaut/serviceman or a robot device) would be required to rearrange and relocate the drill string elements as required.

To minimize the seriousness of this type of failure, a more advanced and flexible robotic arm should be investigated to replace the current manipulator arm on the LDI. This would provide more accurate handling of the drill string components and would also allow the LDI to pick up any components that were mishandled.

3. Exhausting on Board Power Supplies

Most likely the drilling rates for the LDI will be considerably slower than those for conventional drilling on earth. As a result, in the course of drilling to the maximum 30 meter depth in extremely hard rock, it is possible that the power supply on board the LDI will be consumed before the hole is completed.

The inconvenience of this type of failure could be minimized by using a power supply that could be easily replaced in the midst of the drilling operation.

Furthermore, future technical advances in power supplies may significantly reduce the likelihood of this type of failure.

4. Failure of Cuttings Ejector System

Failure of the Cuttings Ejector System would probably occur due to two primary causes. The most likely cause would be due to improper electrical connections through the drill string. The root cause of this might be the accumulation of foreign materials (dust) on the connections or possibly wear and plastic deformation of the electrical connectors themselves. A more advanced electrical connector design for the LDI drill string should be pursued to increase the reliability of the cuttings ejector system.

A second possible cause of failure would be due to excessive bowing of the drill string assembly. This type of deflection would prevent the cuttings from having a straight path to pass through as they were ejected from the bottom of the drill string. The cuttings would then collide with the inner walls of the drill string, loose momentum, and fall back down to the drill bit. Further investigation of the current design for the drill rods should be conducted to evaluate the potential for excessive bowing of the drill string.

Currently, this type of failure, regardless of the cause, would require the drilling operation to be stopped and the drill string disassembled. A diagnostic investigation of the system components would then be required to identify and correct the problem.

SECTION 5 OPERATING HAZARDS

The most serious operating hazard involved with the LDI is the ejected cuttings from the Cuttings Ejector System. Under the current design, the rock cuttings are propelled from the bottom of the drill string, up through the LDI platform, and are deflected away and downward from the LDI and Lunar Arthropod. In this way, the cuttings fall in a pile at one specific location, rather than being scattered in totally arbitrary directions. An individual or piece of equipment entering the path of the ejected cuttings would risk being pummeled by small rock cuttings. To minimize this hazard, motion sensors could be employed to detect anything moving toward the location of the rock cuttings pile. The drilling process would then be halted until the area was clear.

A second operating hazard would be the presence of an astronaut beneath the LDI when the drill rod manipulator arm was moving. Once again, motion sensors or possibly a series of light curtains could be implemented to detect a foreign presence in the manipulator arm work envelope.

SECTION 6 CLOSING REMARKS

6.1 RECOMMENDATIONS

The following is a list of recommendations for improvements in the LDI design and for further development of the lunar drilling process.

1. Drill bit life and drilling efficiency could be enhanced by continuously monitoring the drill bit temperature. A knowledge of the instantaneous drill bit temperature would give advanced warning of impending drill bit failure and would allow drill rotation speeds to be optimized for minimum drill bit wear.

2. A more advanced system of electrical connections needs be developed for the drill rod connecting joints. The current design has some potential reliability problems and is limited in the number of different signals it can transmit. Further development of the electrical connections would be required if item #1 (above) is to be accomplished.

3. The current manipulator arm should be developed into a more flexible and agile robot arm. This would enable the arm to complete the current drill string

manipulating tasks more efficiently and accurately, plus the arm could be used for new and more complicated tasks that are as of yet undefined.

4. The current LDI design could easily be modified to take core samples. A core sampling element that features an internal carrousel of smaller core sampling bits and containers should be developed. A core sampler would be indexed to the center of the sampling element and locked into place. The drilling operation would continue until the sample is collected. The loaded core sampler would then be released and another sampling element would be indexed into place. The process would be repeated until all of the core samplers were loaded. The core sampling element would then be removed from the hole and the samples withdrawn.

5. It may necessary to develop a hole collar for the LDI. When drilling in especially loose ground, the soil around the top of the hole may tend to cave in. A collar that could be driven a short depth into the hole would support the surrounding soil and alleviate the cave-in problem.

6.2 CONCLUSIONS

This report has proposed a design for a lunar drilling implement to be used in conjunction with a lunar arthropod. The implement described here, known as the LDI, will be capable of drilling a hole of approximately 100 mm in diameter with a maximum depth of 30 m. The LDI incorporates features that enable it to conduct dry drilling operations on the lunar surface without the constant presence of an astronaut / operator.

Within the time constraints available to work on this project, it is extremely difficult, if not impossible, to conceive and develop a complete and detailed design for a system as complicated as the Lunar Drilling Implement. Admittedly, this report does not cover every detail needed to develop the LDI. However, the authors of this report feel that there are several unique components of the LDI that deserve consideration in future lunar drill designs. In summary, the most promising components of the LDI design are:

1. Curvilinear Synchronous Motor
2. Heat Pipe Drill Bit Cooling System
3. Rock Cuttings Ejector System
4. Drill Rod Storage and Retrieval System
5. Drill Rod Connecting Joint

Although the final lunar drill design may be considerably different than the one proposed in this report, hopefully it will make use of some of the features discussed here.

ACKNOWLEDGMENTS

The Lunar Drill Group would like to thank the following people for their guidance and valuable assistance in the development of our design project.

Jim Brazell, Georgia Tech

Dr. Colwell, Georgia Tech

Dr. Davey, Georgia Tech

Karl A. Faymon, NASA - Lewis Research Center

Gary Kelley

Calvin Miller, Bell Labs

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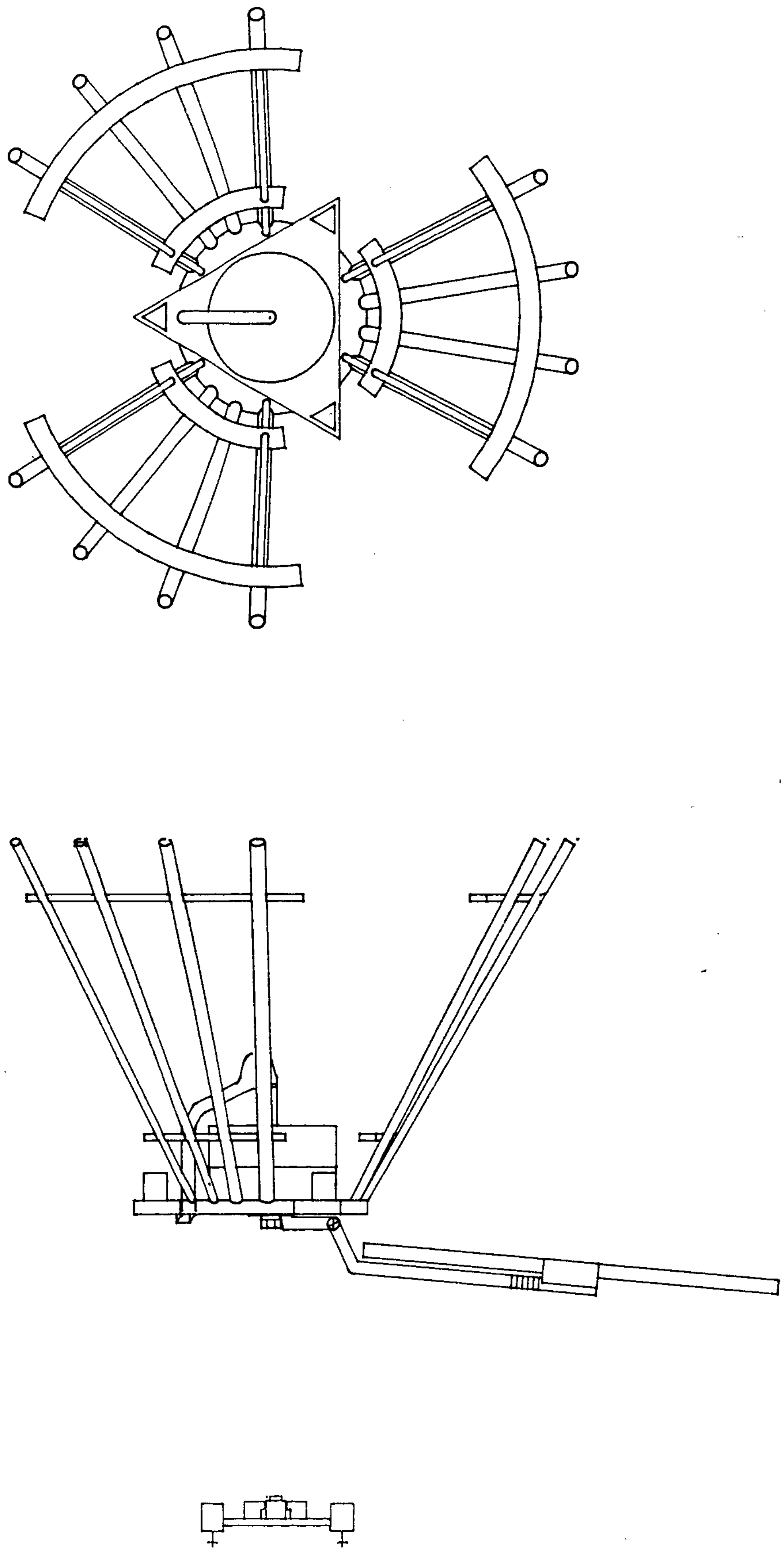
12. Waston, James F., "Materials at Cyrogenic Temperatures," Materials for Missiles and Spacecraft, McGraw Hill, New York, 1963.

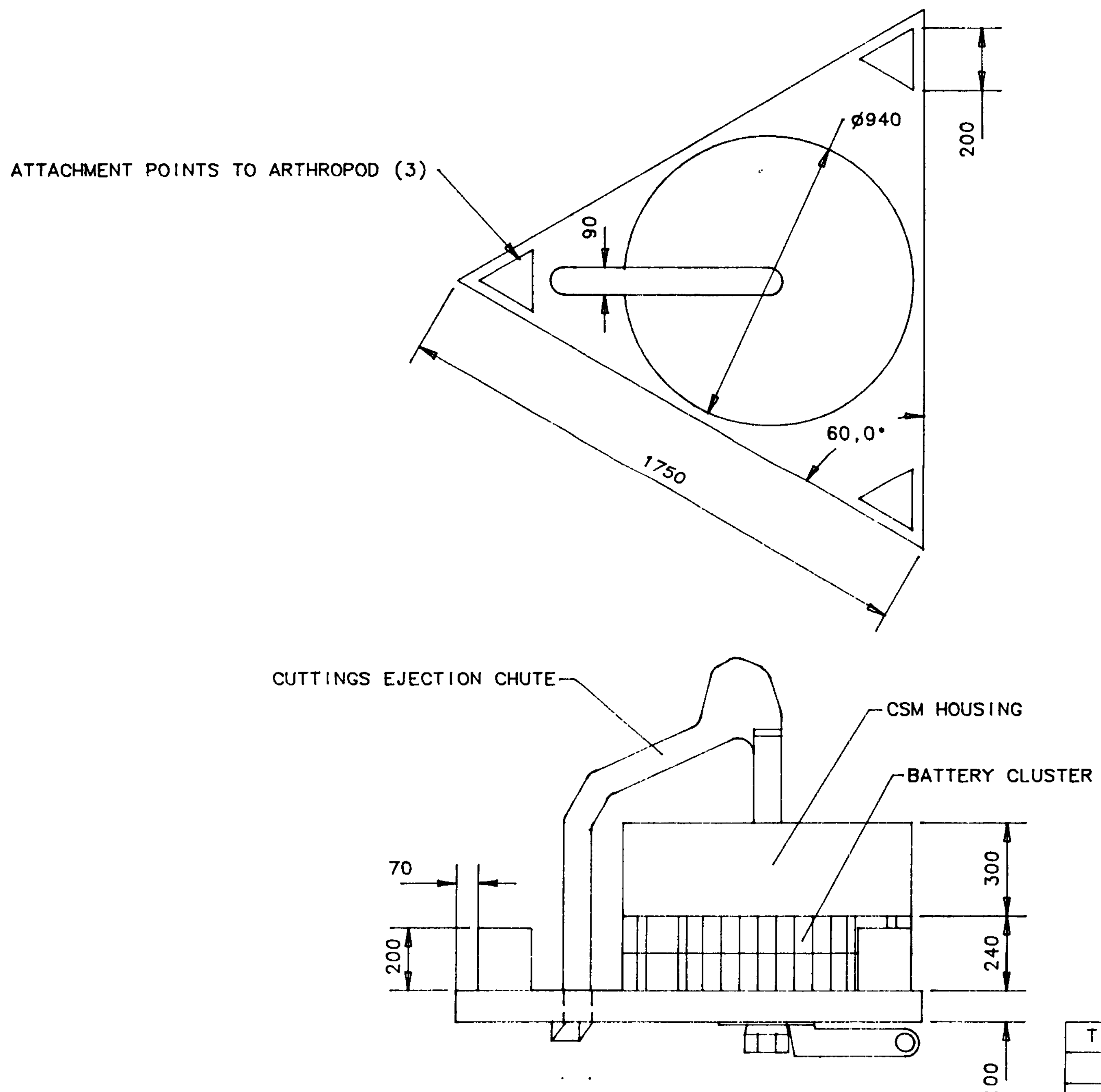
APPENDIX A

DRAWINGS AND FIGURES

DRAWINGS



TITLE DESIGN OVERVIEW		
LUNAR DRILLING IMPLEMENT		
DATE 03/11/87	DRAWN GSM	DWG NO 1



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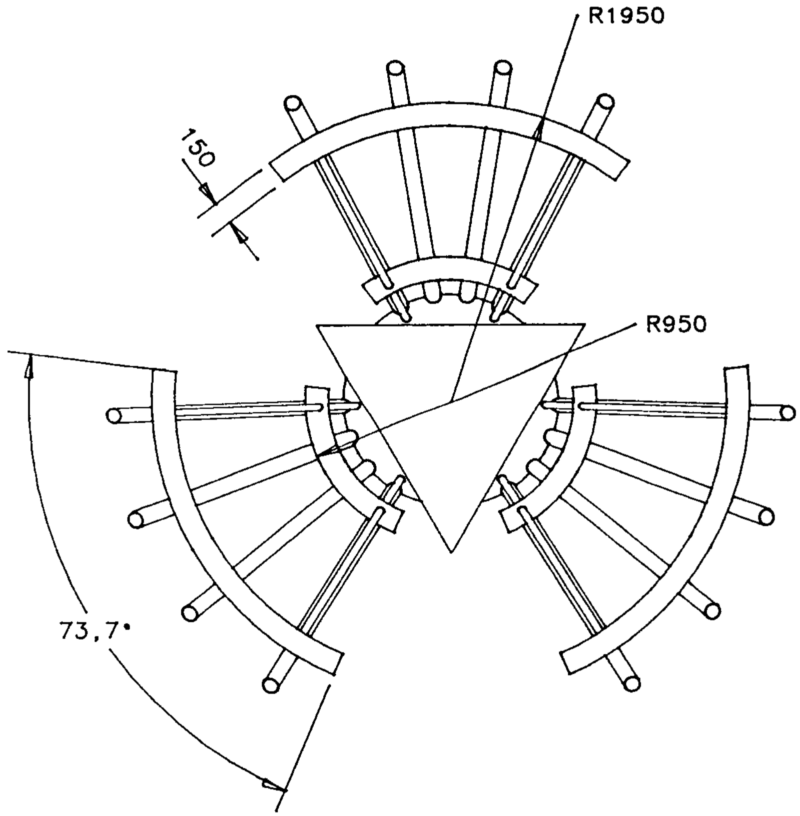
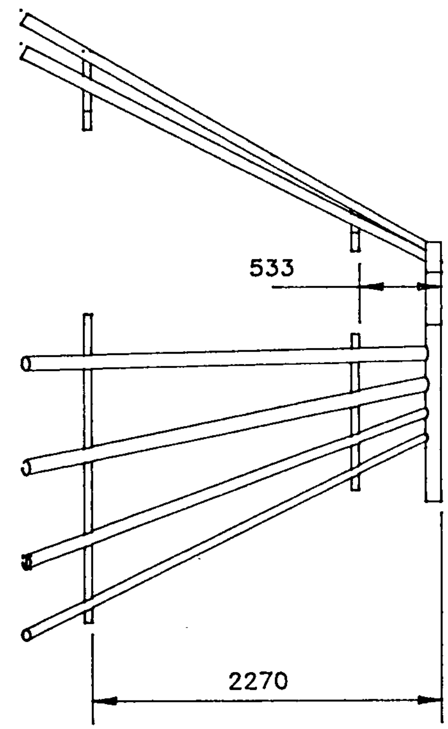
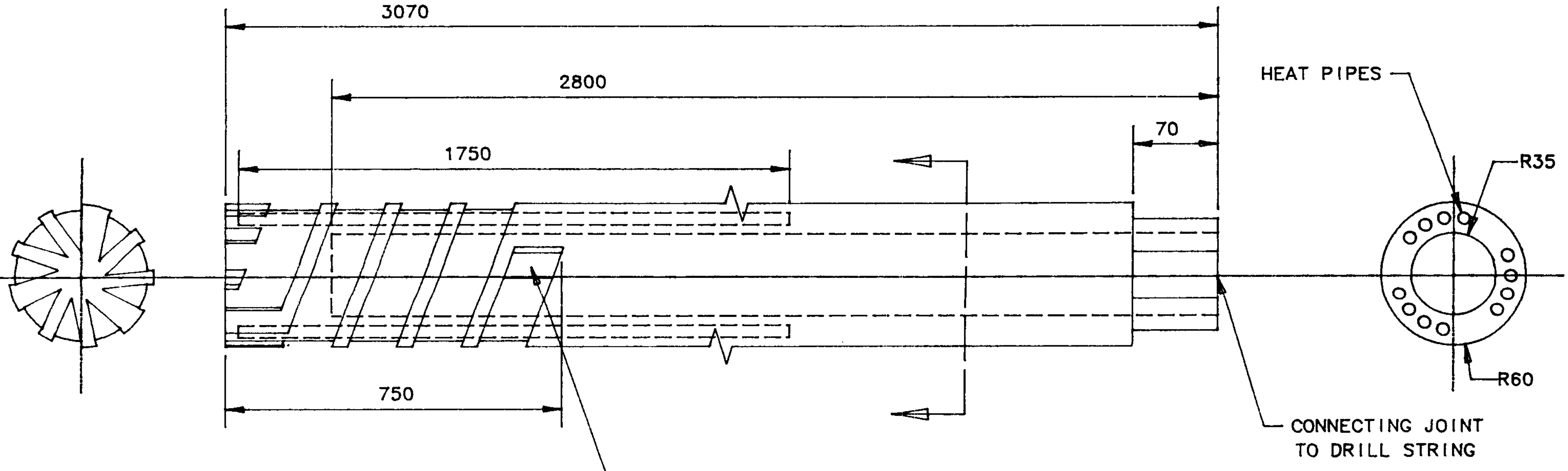
LUNAR DRILLING IMPLEMENT		
DATE 03/10/87	DRAWN BY: GSM	DWG NO 2





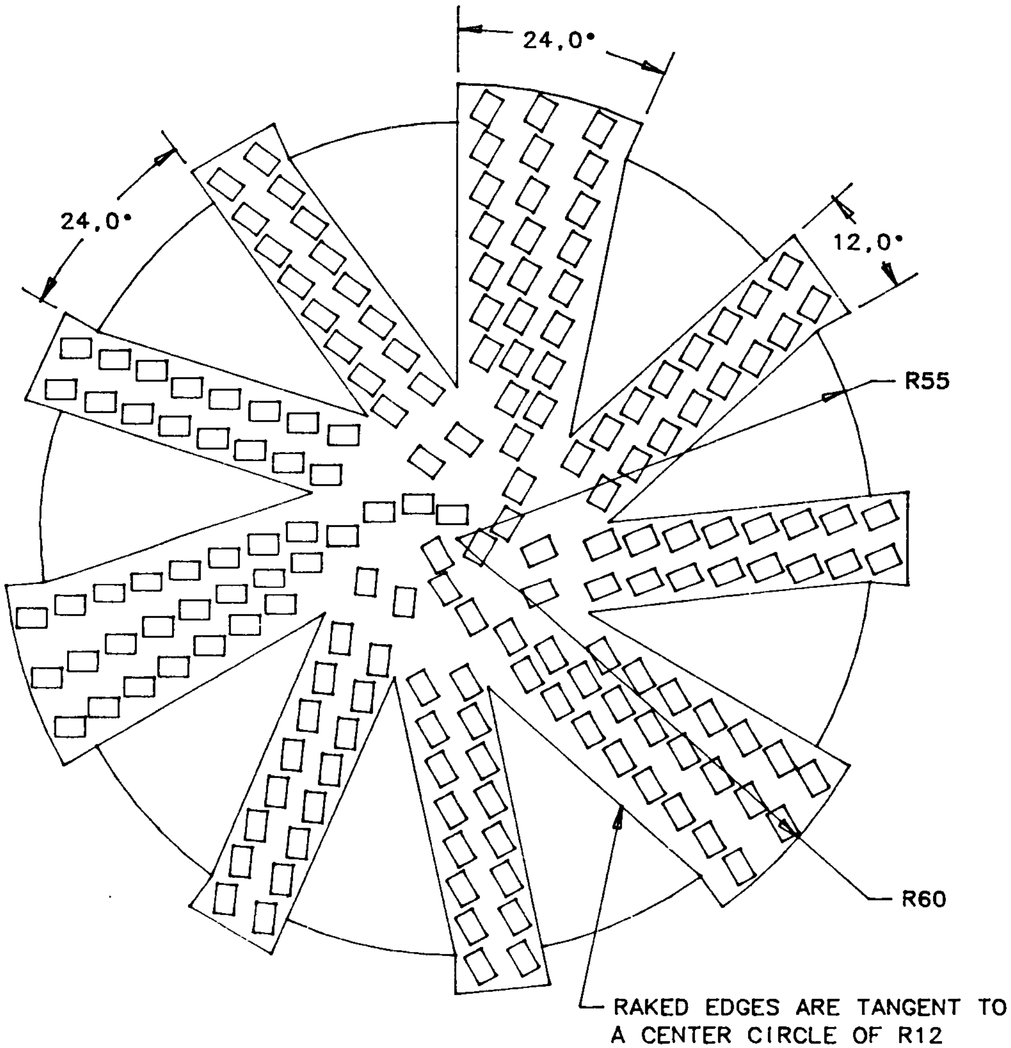
TITLE TRAYS	
LUNAR DRILLING IMPLEMENT	

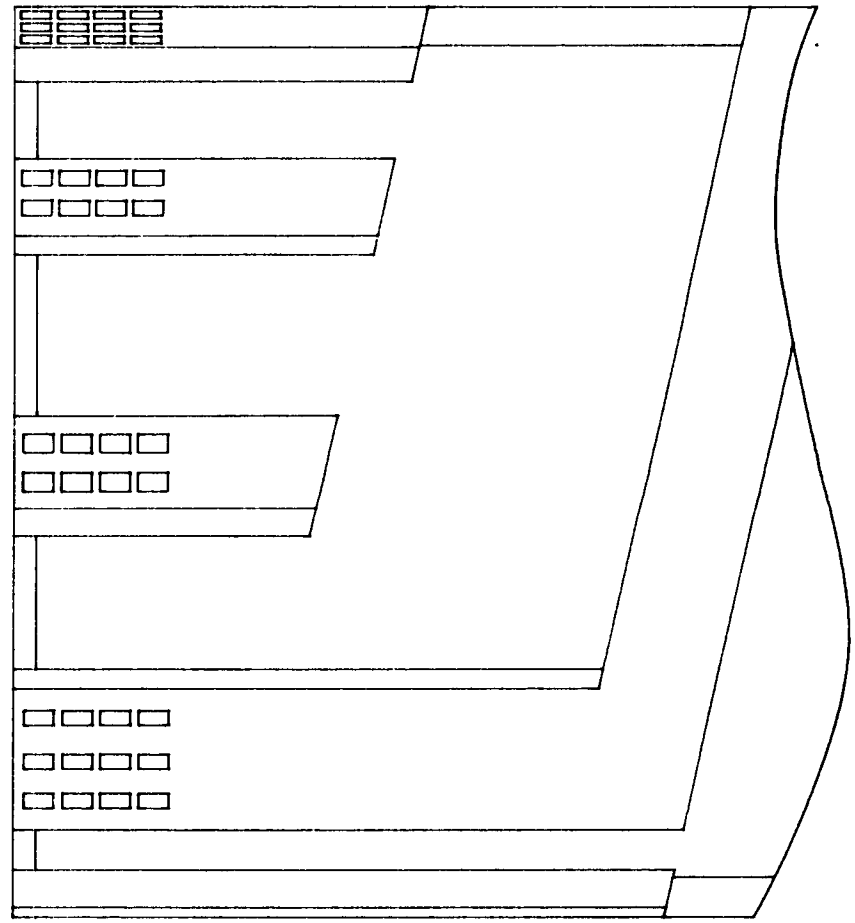


AUGER FLIGHT DIMENSIONS:

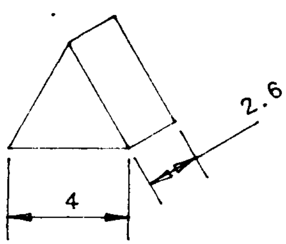
1. TRIPLE THREADED AUGER FLIGHT
2. AUGER ANGLE OF 15 DEGREES
3. AUGER DEPTH - 3 mm
4. AUGER DIAMETER - 119 mm

TITLE	DRILL BIT ELEMENT	
LUNAR DRILLING IMPLEMENT		
DATE 3/8/87	DRAWN BY T.B.	DRWG NO 4



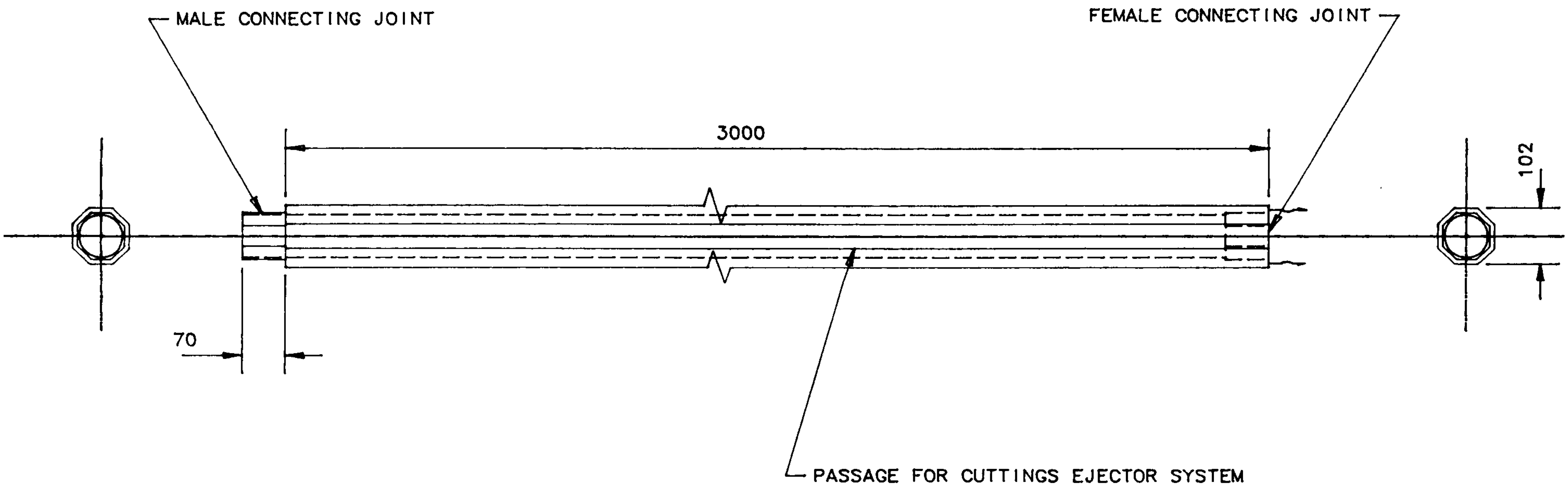


□ INDICATE LOCATION OF CUTTING DIAMONDS

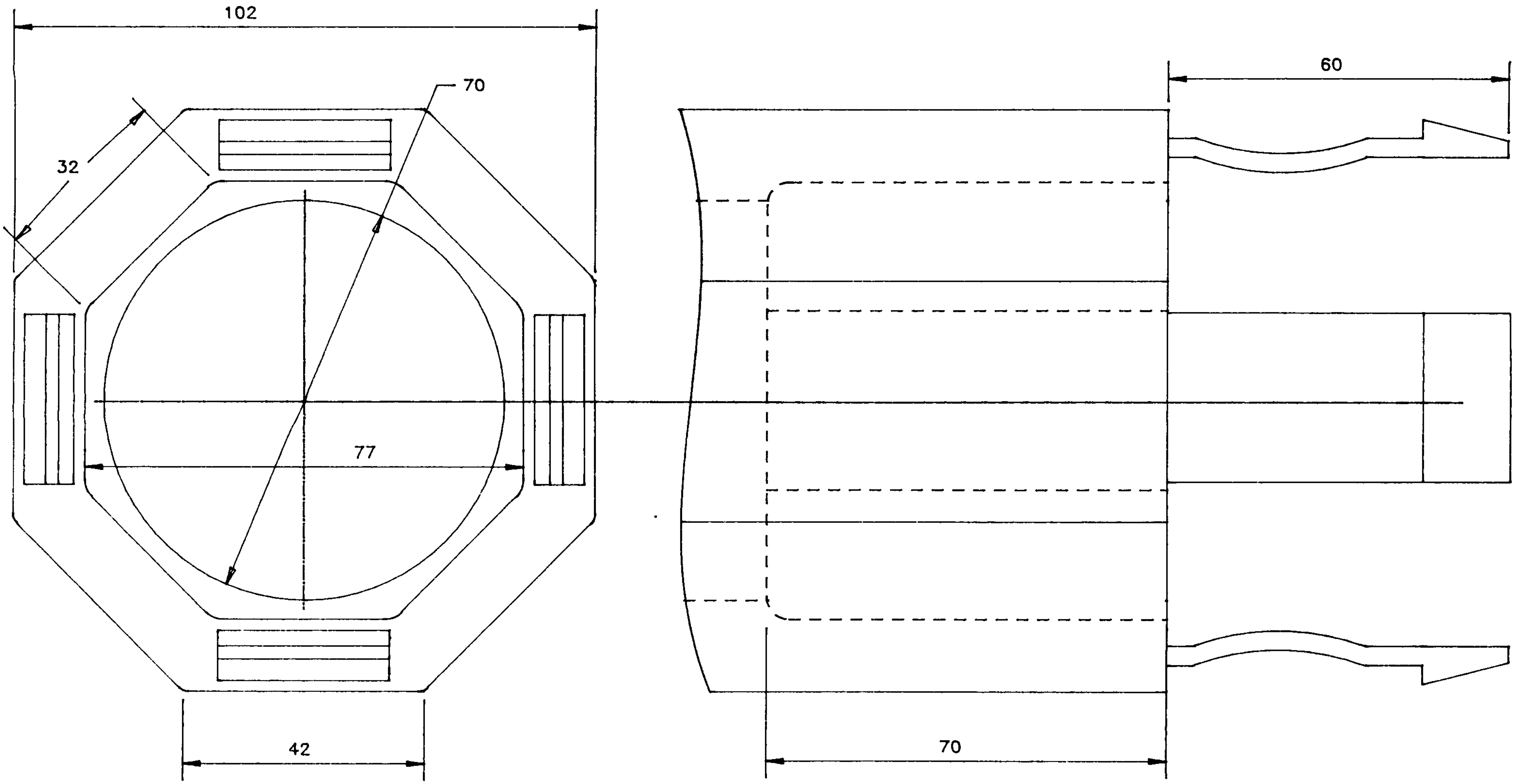


CUTTING ELEMENT DETAIL

TITLE DRILL BIT DETAIL		
CUTTING ELEMENT LOCATIONS		
LUNAR DRILLING IMPLEMENT		
DATE 3/7/87	DRAWN BY T.B.	DRWG NO 5

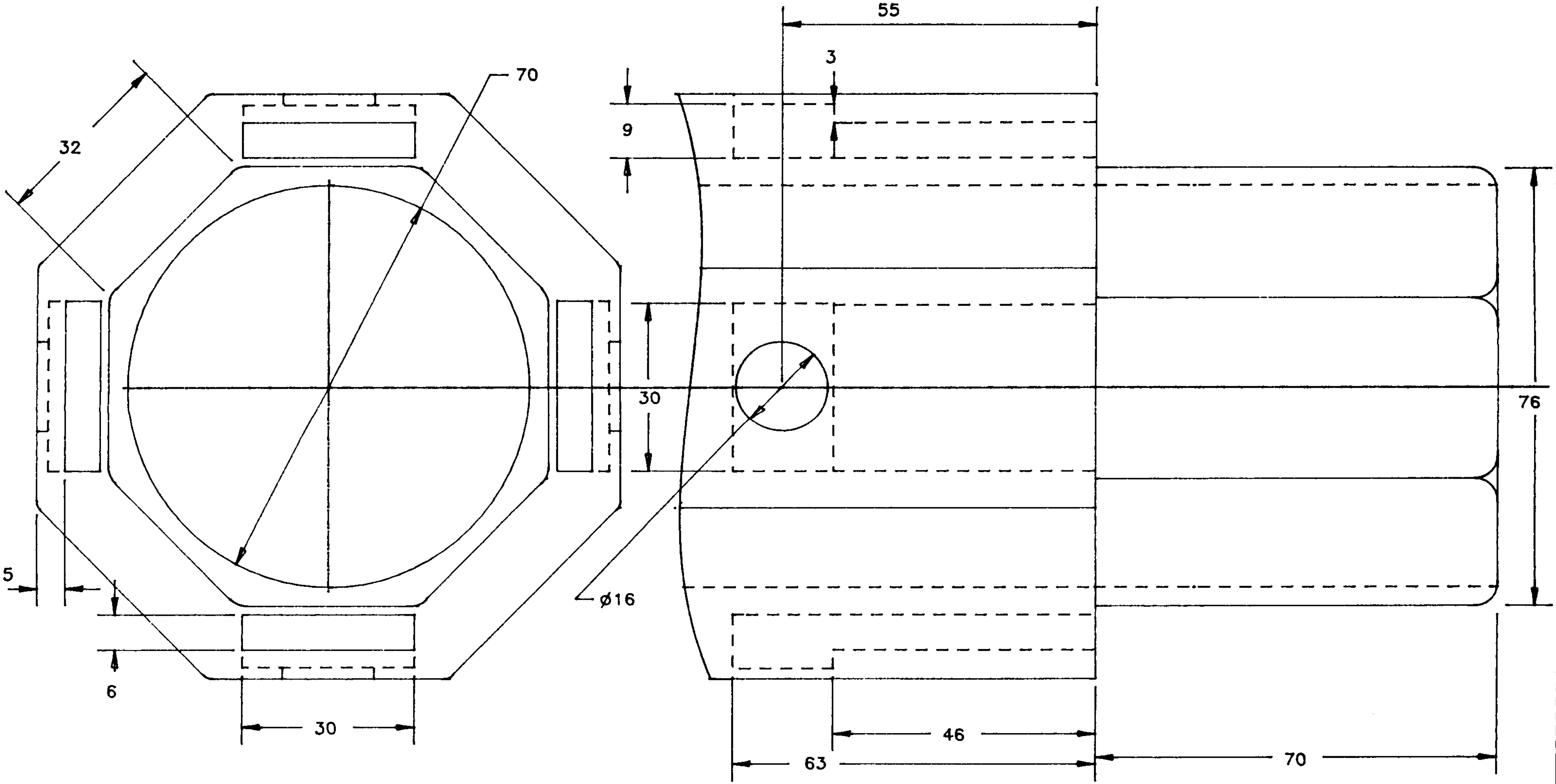


TITLE: DRILL ROD		
LUNAR DRILLING IMPLEMENT		
DATE 3/7/87	DRAWN BY: T.B.	DRWG NO. 6

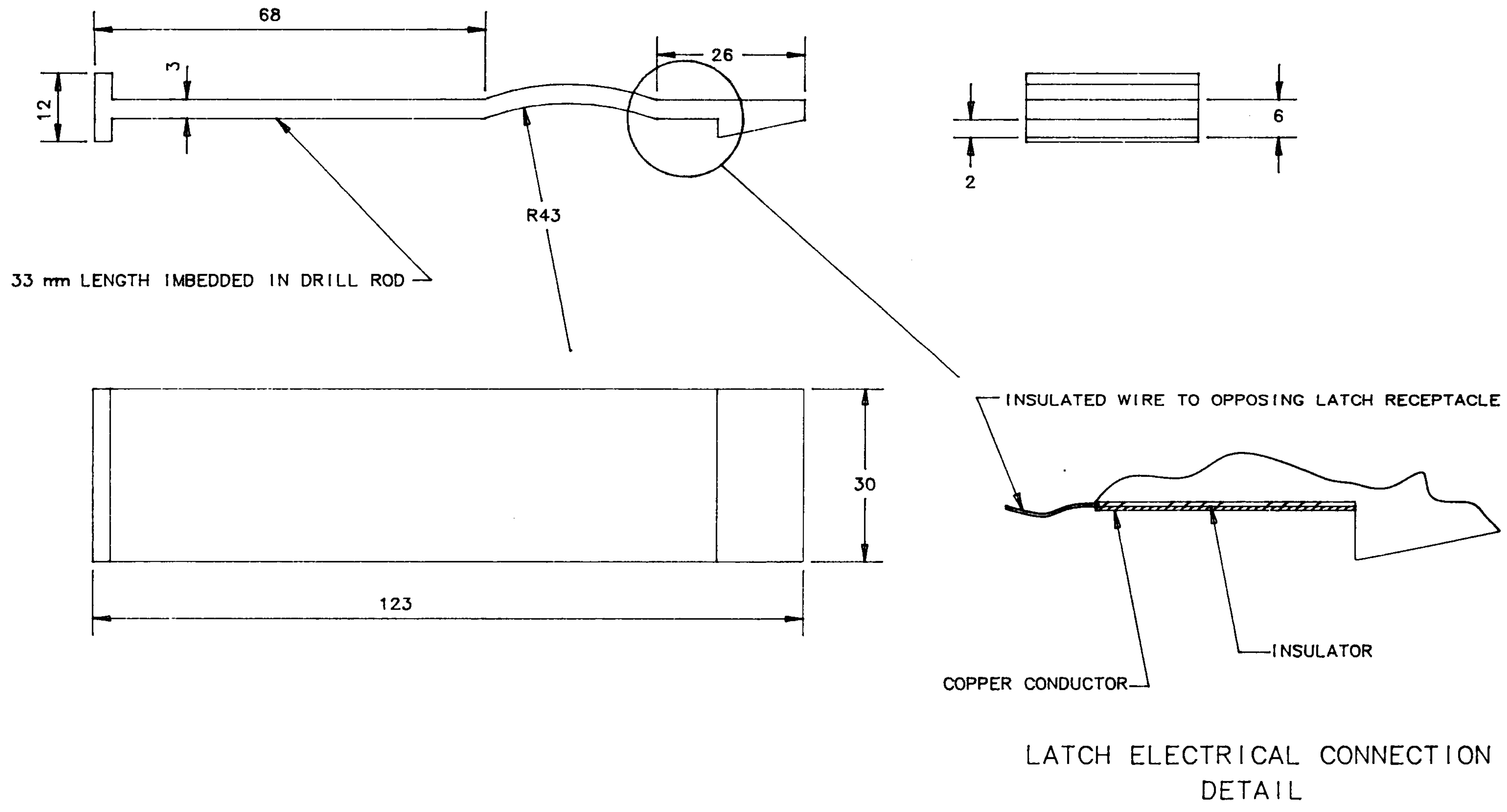


NOTE - DETAILS OF FINGER LATCHES SHOWN
ON DRWG. NO 7

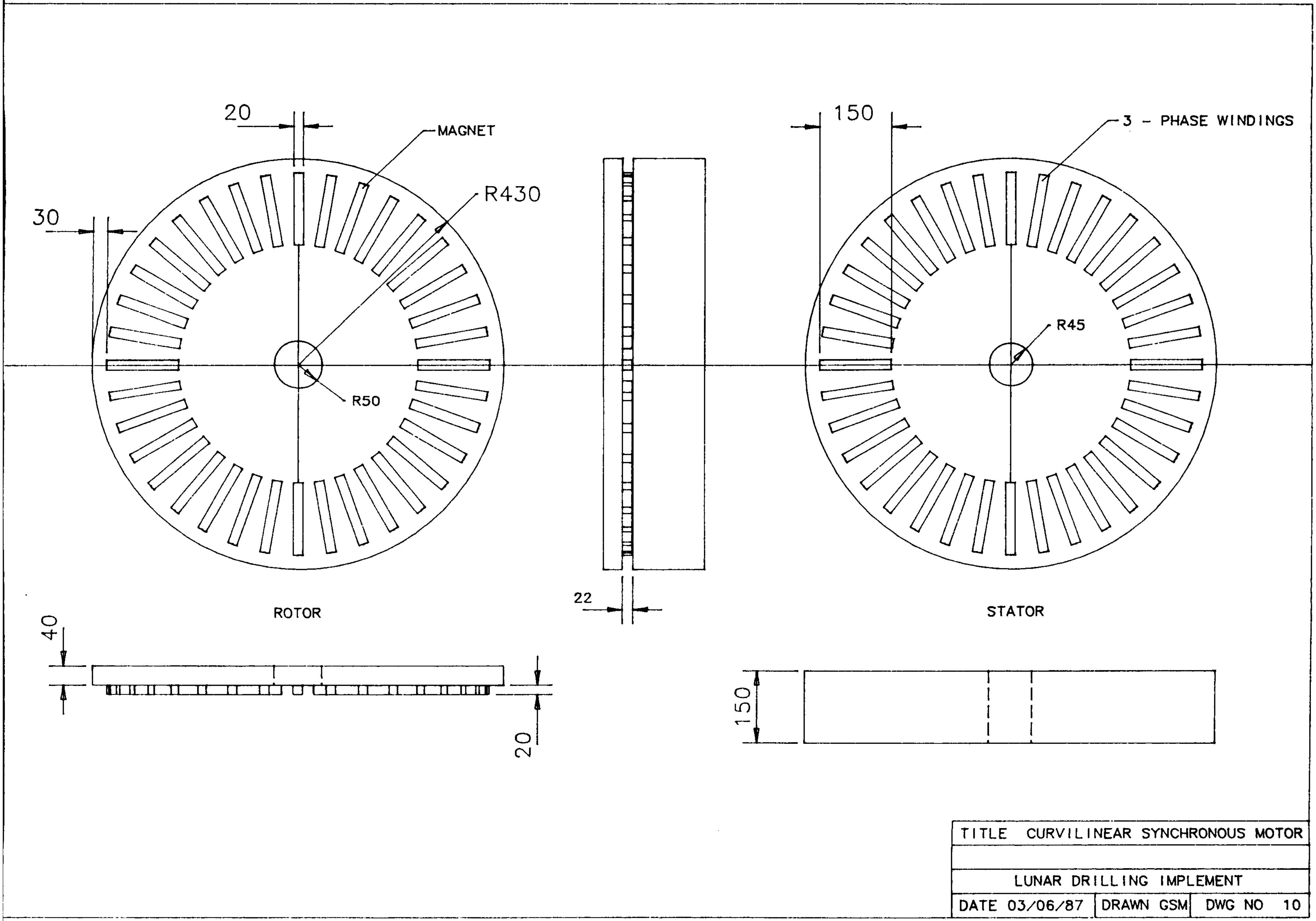
TITLE: DRILL ROD FEMALE CONNECTING JOINT		
LUNAR DRILLING IMPLEMENT		
DATE 2/27/87	DRAWN BY: T.B.	DRWG NO. 7

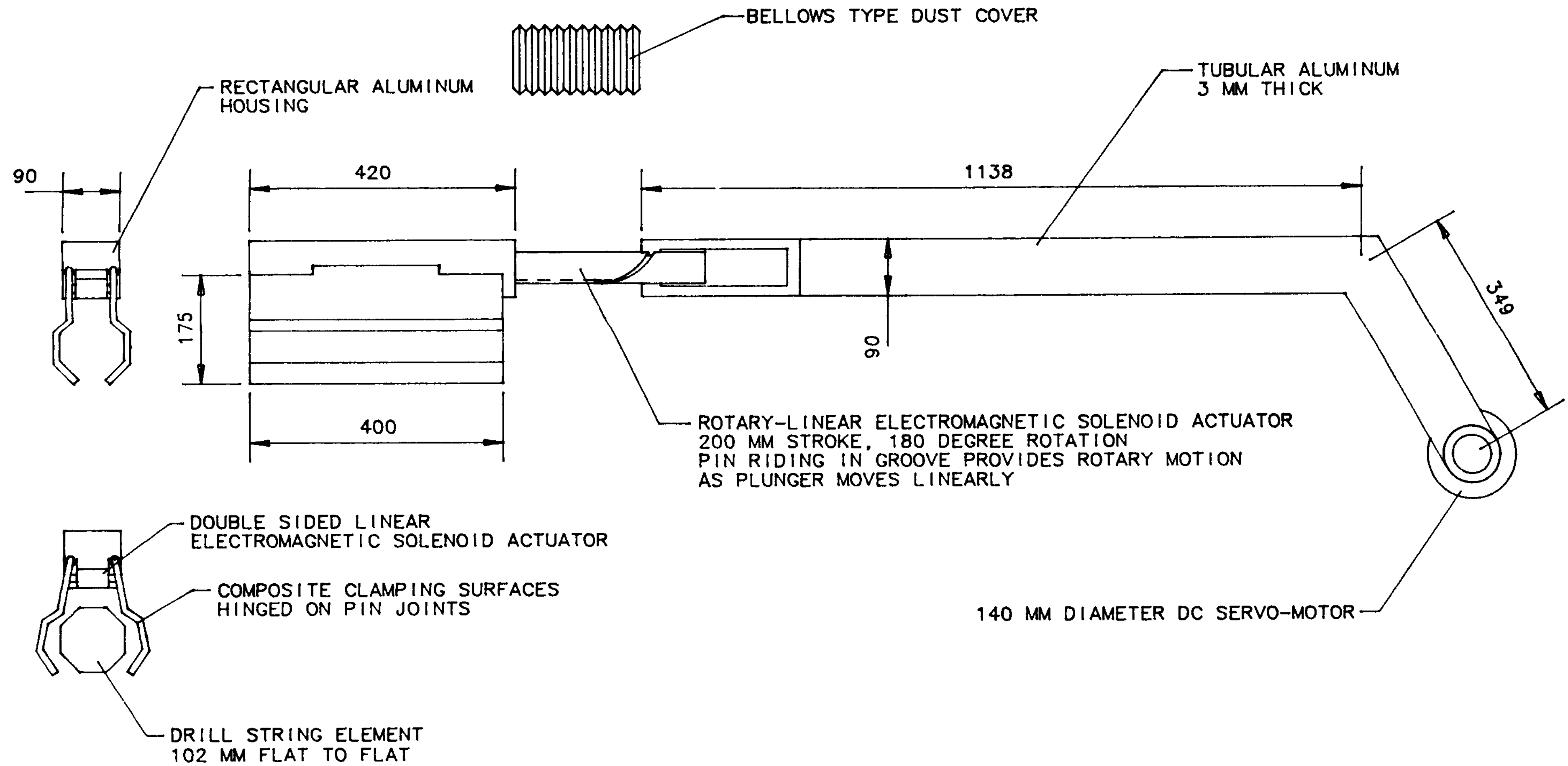


TITLE: DRILL ROD MALE CONNECTING JOINT		
LUNAR DRILLING IMPLEMENT		
DATE 2/28/87	DRAWN BY: T.B.	DRWG NO. 8

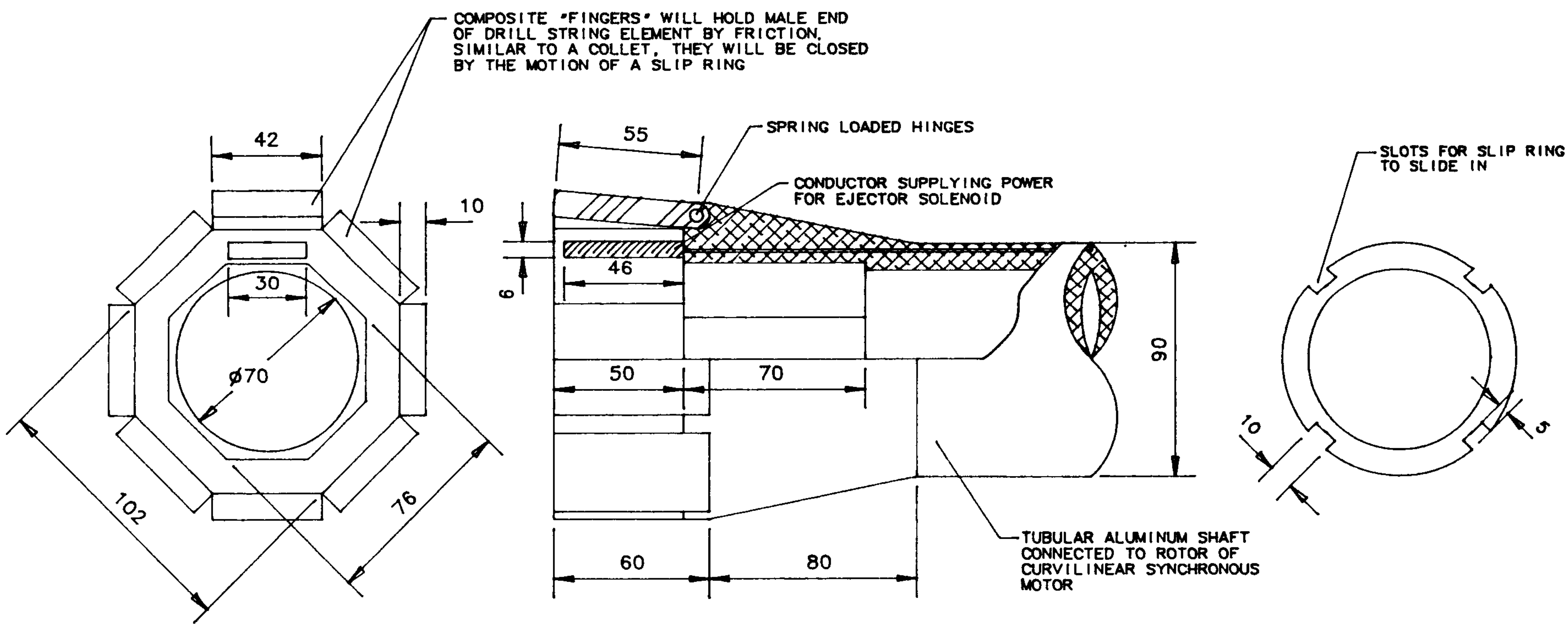


TITLE: FINGER LATCH DETAIL		
LUNAR DRILLING IMPLEMENT		
DATE 2/27/87	DRAWN BY: T.B.	DRWG NO. 9

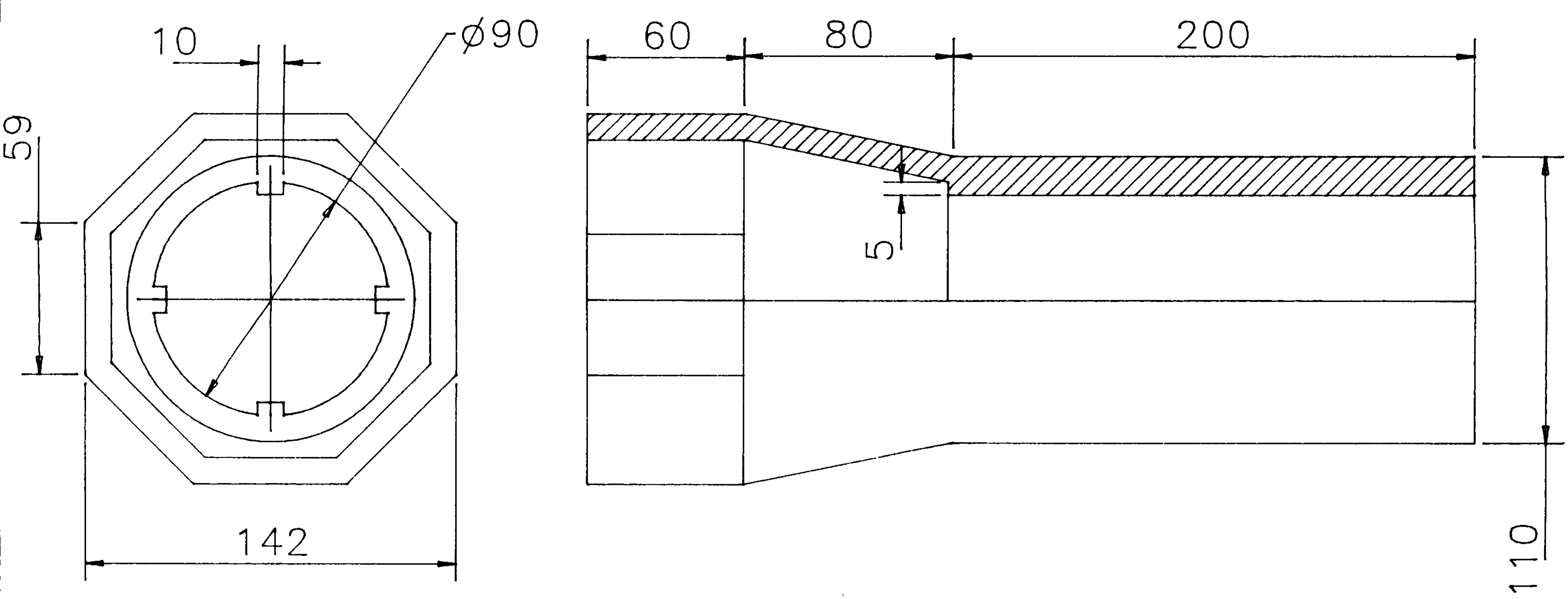

20
MAGNET
R430
30
R50
ROTOR
40
20
22
150
3 - PHASE WINDINGS
R45
STATOR
150
TITLE CURVILINEAR SYNCHRONOUS MOTOR
LUNAR DRILLING IMPLEMENT
DATE 03/06/87
DRAWN GSM
DWG NO 10



TITLE MANIPULATOR ARM		
LUNAR DRILLING IMPLEMENT		
DATE 03/06/87	DRAWN GSM	DWG NO 11



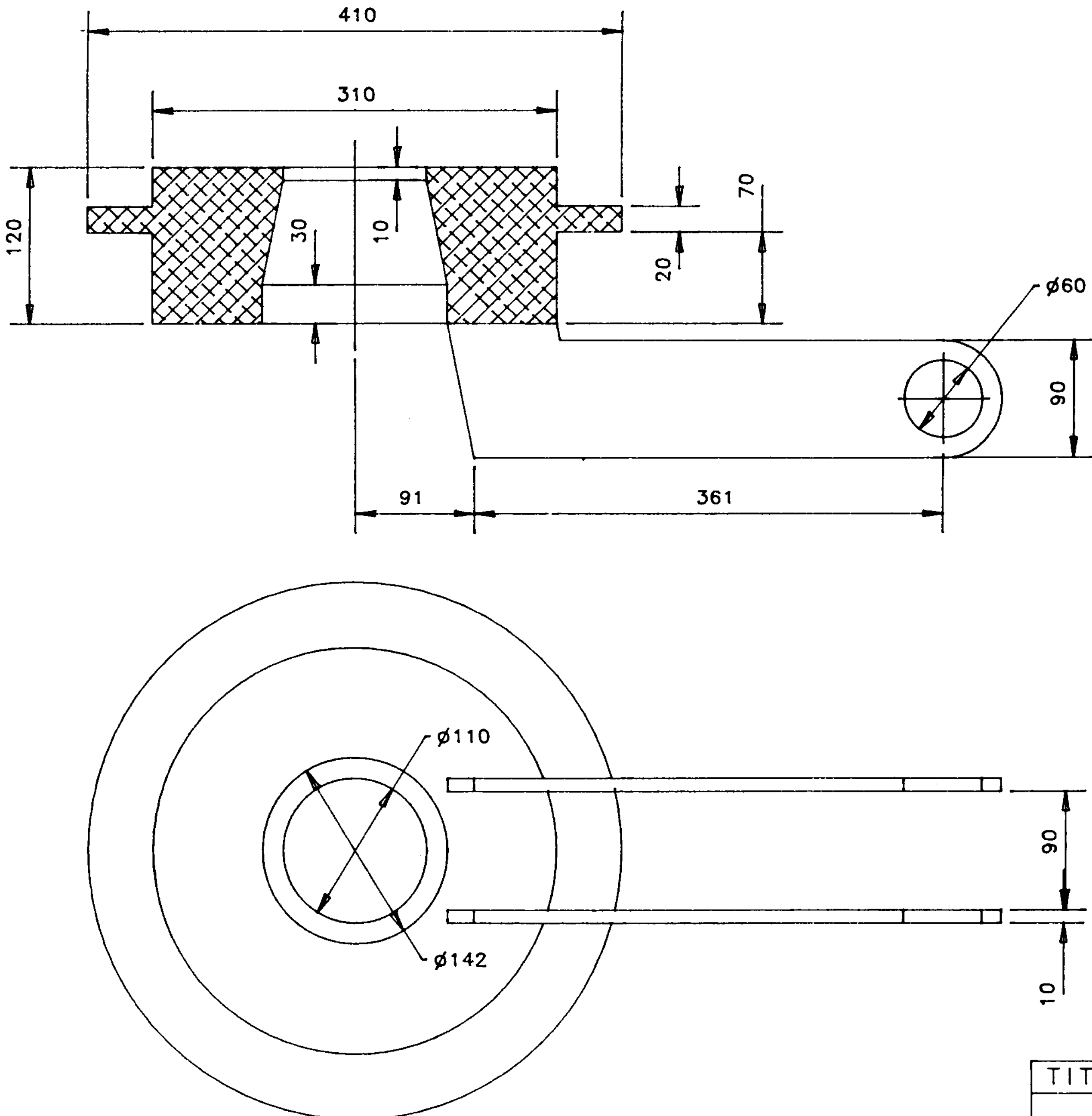
TITLE CHUCK		
LUNAR DRILLING IMPLEMENT		
DATE 03/07/86	DRAWN GSM	DWG NO 12



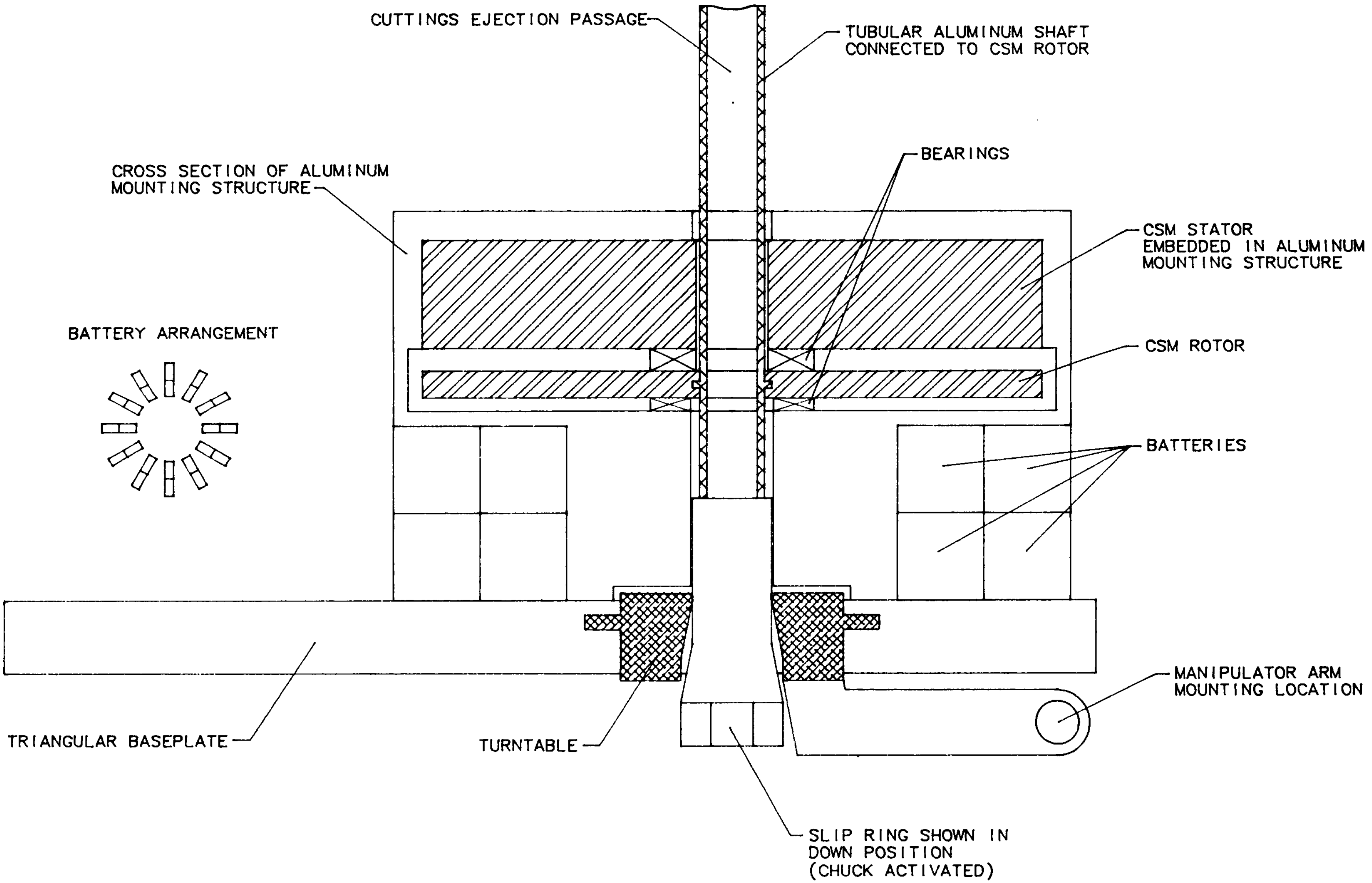
TITLE SLIP RING

LUNAR DRILLING IMPLEMENT

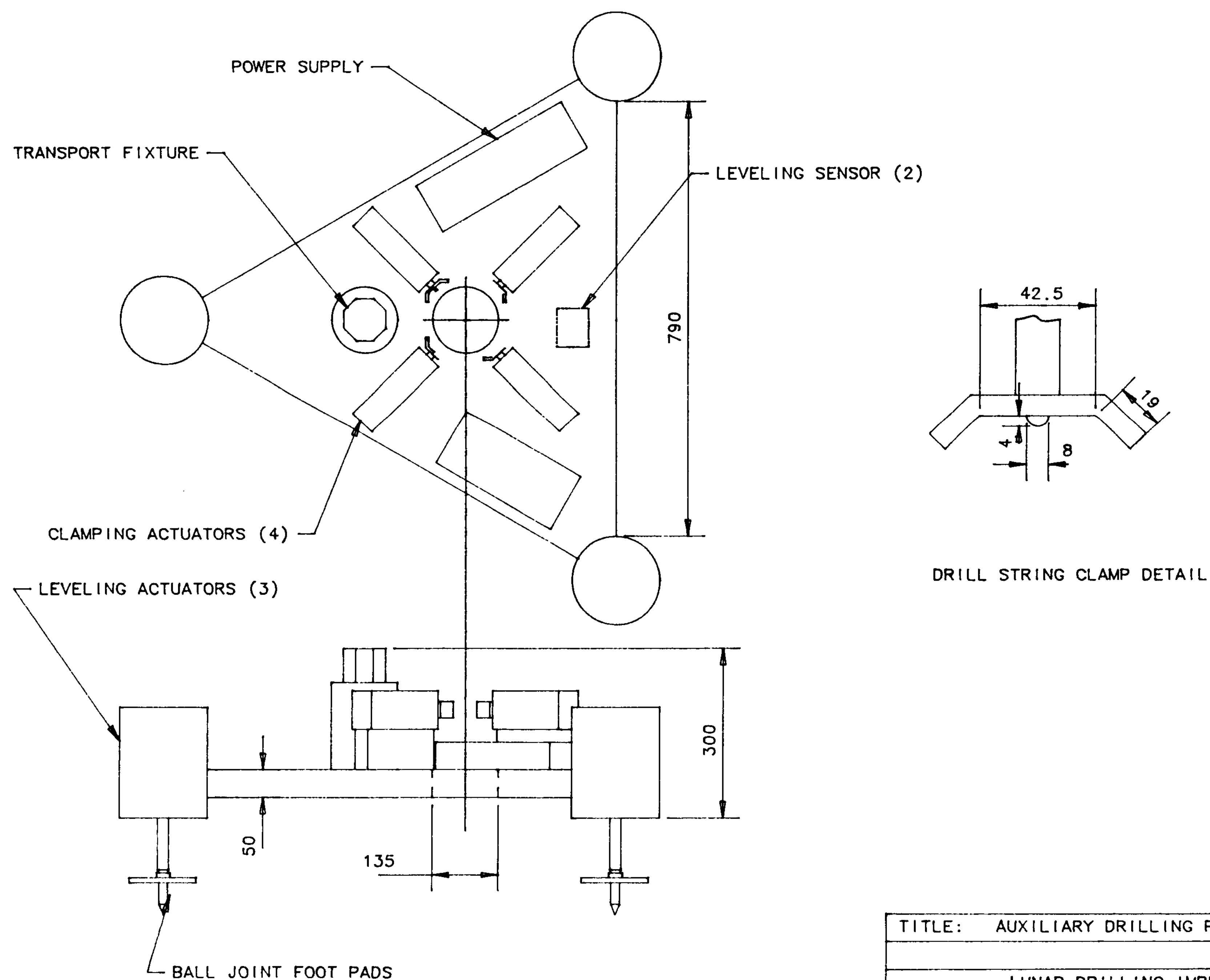
DATE 03/06/87 | DRAWN GSM | DWG NO 13



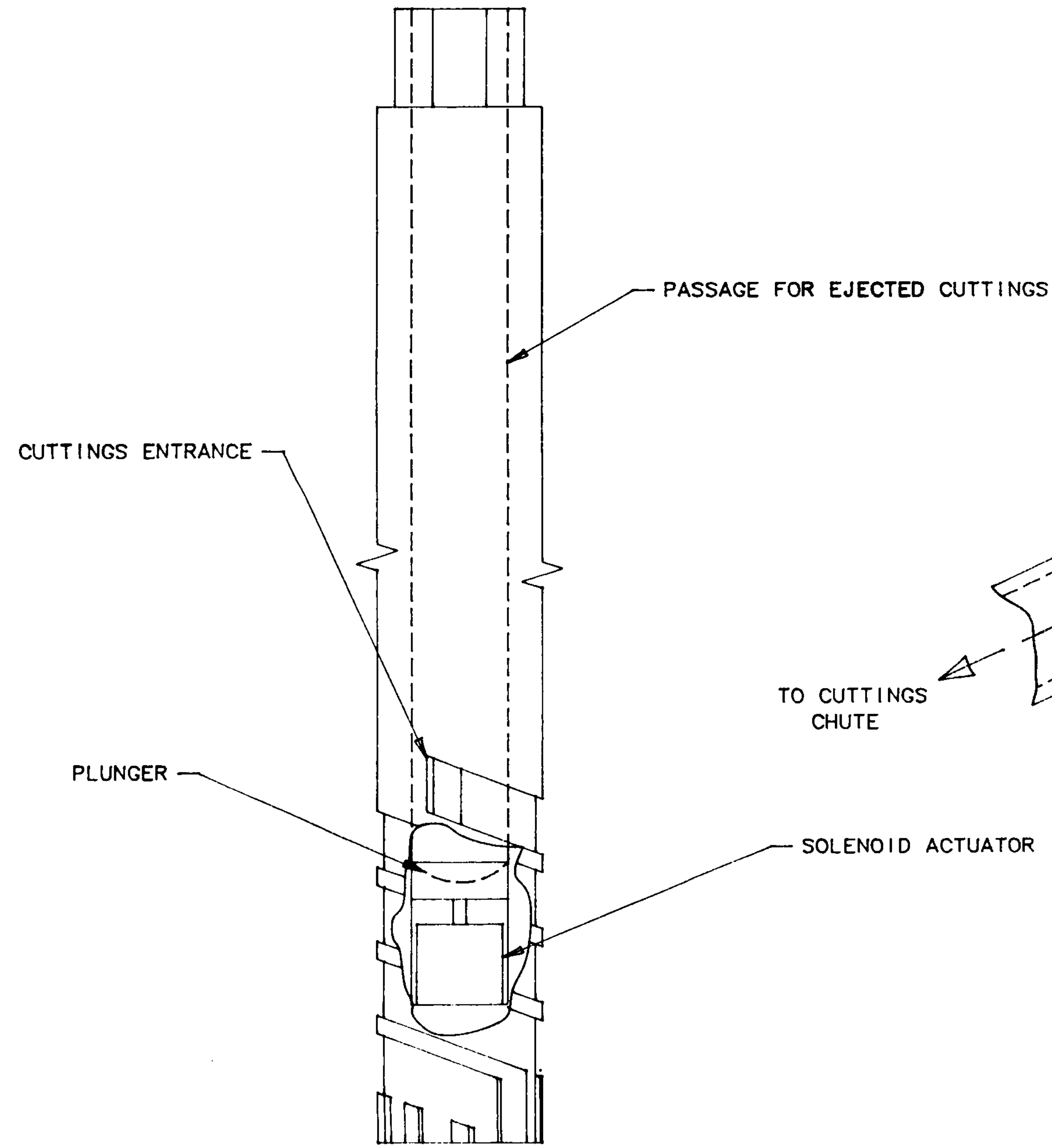
TITLE TURNTABLE		
LUNAR DRILLING IMPLEMENT		
DATE 03/07/87	DRAWN GSM	DWG NO 14



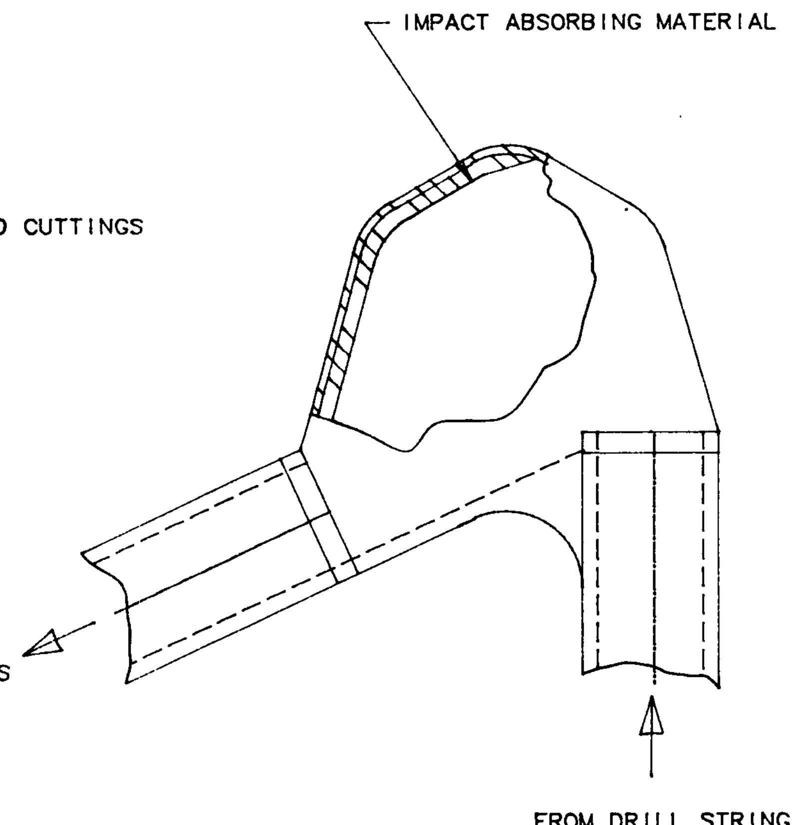
TITLE TRIANGULAR BASE PLATE		
ASSEMBLY		
DATE 03/08/87	DRAWN GSM	DWG NO 15



TITLE: AUXILIARY DRILLING PLATFORM		
LUNAR DRILLING IMPLEMENT		
DATE 3/8/87	DRAWN BY: T.B.	DRWG NO. 16

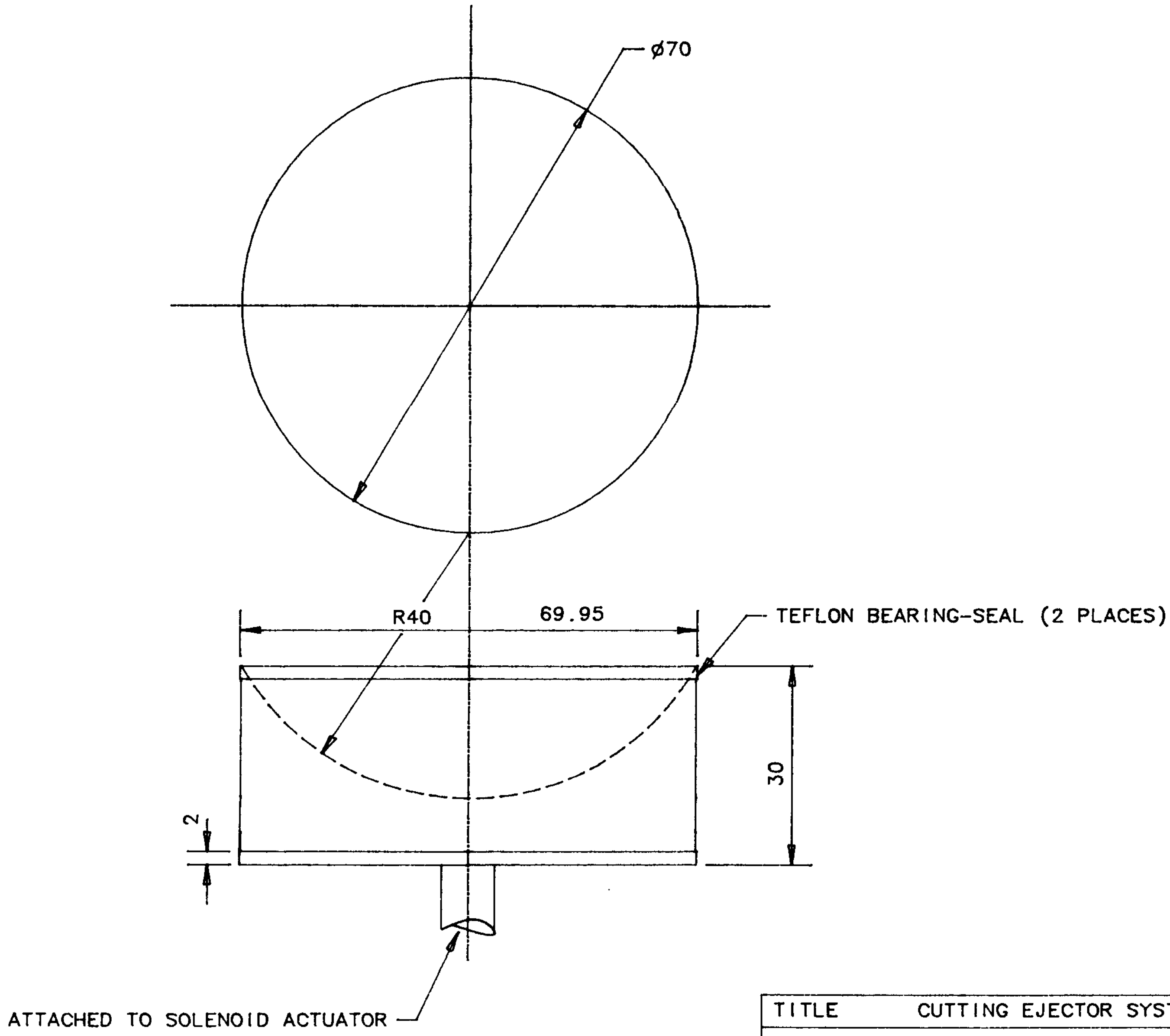


DRILL BIT AND SOLENOID / PLUNGER

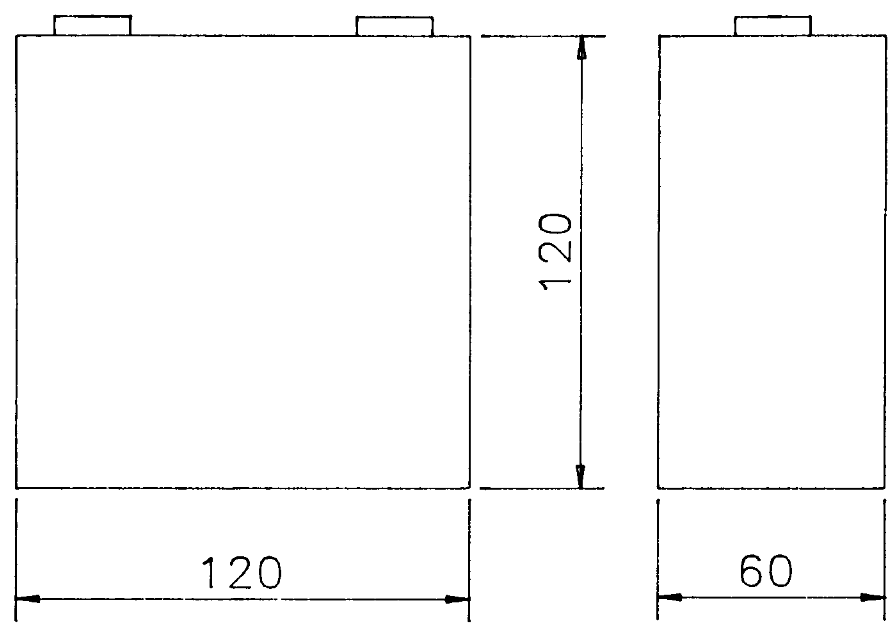


CUTTINGS DEFLECTOR

TITLE CUTTINGS EJECTOR SYSTEM		
LUNAR DRILLING IMPLEMENT		
DATE 3/8/87	DRAWN BY T.B.	DRWG NO 17

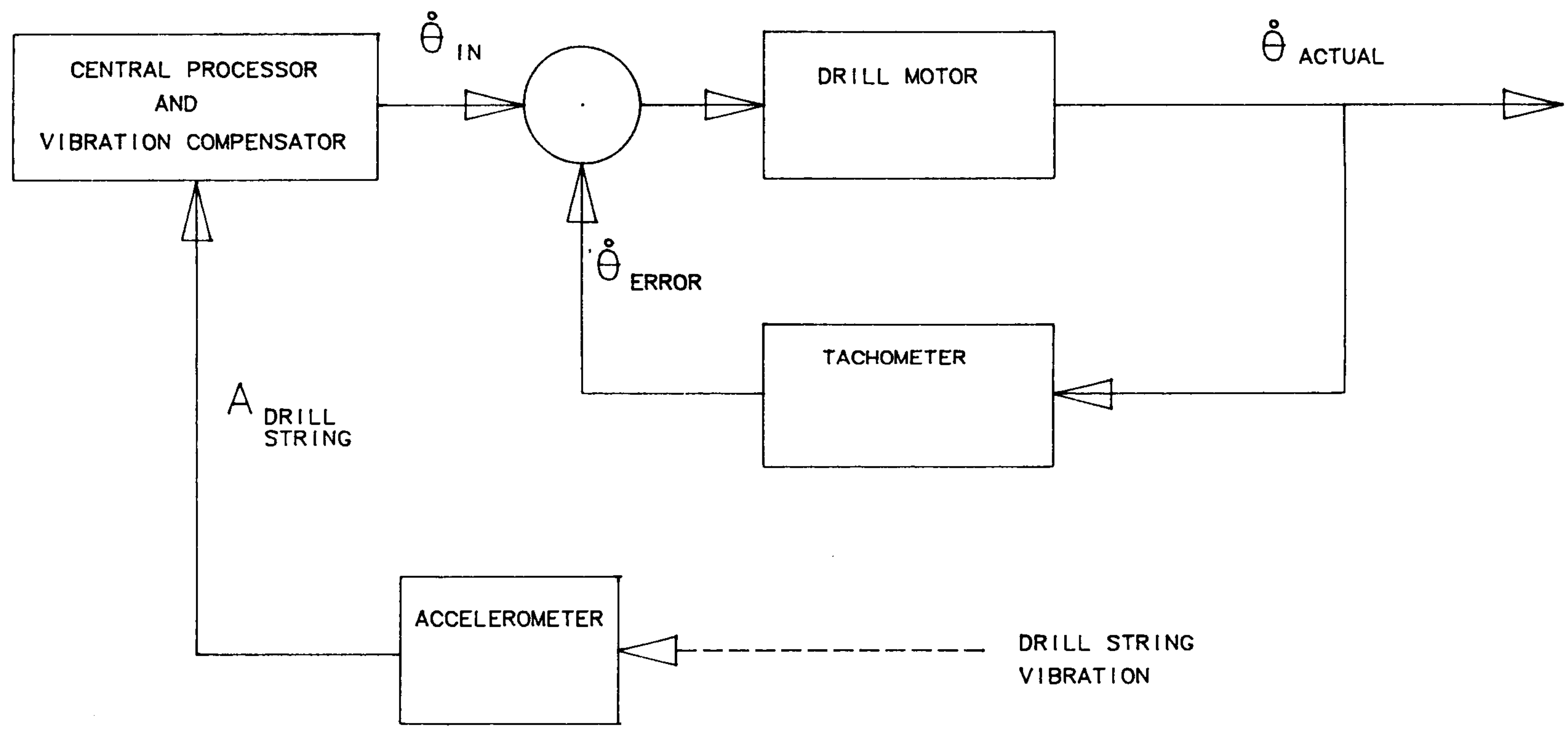


TITLE CUTTING EJECTOR SYSTEM PLUNGER		
LUNAR DRILLING IMPLEMENT		
DATE 3/7/87	DRAWN BY T.B.	DRWG NO 18



MASS = 1.6 Kg

TITLE BATTERY		
LUNAR DRILLING IMPLEMENT		
DATE 03/10/87	DRAWN GSM	DWG NO. 19



$\mathring{\theta}_{IN}$	INPUTED DRILL ROTATION SPEED ADJUSTED FOR MINIMUM VIBRATION
$\mathring{\theta}_{ACTUAL}$	ACTUAL DRILL STRING SPEED
$\mathring{\theta}_{ERROR}$	ERROR BETWEEN $\mathring{\theta}_{IN}$ AND $\mathring{\theta}_{ACTUAL}$
$A_{DRILL\ STRING}$	DETECTED VIBRATION OF DRILL STRING

TITLE: CONTROLS DIAGRAM DRILL STRING SPEED		
LUNAR DRILLING IMPLEMENT		
DATE 3/02/87	DRAWN BY: T.B.	DRWG NO. 20

APPENDIX B

DRILL ROD CALCULATIONS

Motor and thrust data were estimated through extrapolation of data collected during previous lunar drilling operations.

power = 8 hp

speed = 700 - 1000 rpm

torque = 42 ft-lbf = 58 N-m

axial thrust = 600 lbf = 2724 N

In the following calculations the material properties are for Celion 6000/PMR-15 graphite fiber reinforced composite. Values are approximated for unidirectional fibers with some ±45 degree plies for torsional stiffness. Composite material properties are commonly estimated through the use of the rule of mixtures. In this method the contribution to the overall property value, by a constituent, is weighted by its volume fraction.

Mechanical Properties

Elastic Modulus

$$E = VfEf + VmEm \qquad (1.1)$$

$$E = (.6)(34 * 10^{6}) + (.4)(4.5*10^{6})$$

$$E = 22 * 10 \text{ psi}$$

The longitudinal and torsional stresses were estimated using conventional analysis methods for composite materials. Both the longitudinal and torsional stresses were found to be less than several hundred pounds per inch.

Buckling is a major concern due to the depth of drilling required. In calculating the critical buckling load the inscribed diameter of the octagon cross-section was used to simplify calculations.

$$Pcr = \frac{C\pi^2 EI}{L^2} \qquad (1.2)$$

Where

$C = 1$ (for both ends of column fixed)

$L = 30$ meters $= 1181$ inches

$E = 22 * 10^6$ psi $= 152$ GPa

$I = \pi/64\ (D^4 - d^4)$

D = diameter of inscribed circle of octagon

$D = 102$ mm $= 4.02$ in

d = inside diameter $= 70$ mm $= 2.76$ in

$I = 413.5 * 10^4\ mm^4$

$I = 10\ in^4$

$$Pcr = \frac{(1)(\pi^2)(22 * 10\ psi)(10\ in\ )}{(1181\ in\ )}$$

$Pcr = 1577$ lbf

Mass Properties

mass of drill string

$m = \rho AL$

ρ = density = .058 lbm/in = $1.608 * 10^{-6}$ kg/mm

L = 1181 in = 30 m

A = area = Aoctagon - Acircle

A = 8604 mm^2 = 13.33 in^2

m = 913 lbm = 415 kg = 28.4 slugs

weight of drill string on earth

We = (28.4 slugs)(32.2 ft/sec) = 914 lbf

We = (415 kg)(9.8 m/sec) = 4067 N

Weight of drill string on moon

Wm = (28.43 slugs)(5.37 ft/sec) = 153 lbf

Wm = (415 kg)(1.63 m/sec) = 676.5 N

Thermal Properties

Thermal properties will be approximated using the rule of mixtures.

Longitudinal Conductivity

$$K = VfKf + VmKm \tag{1.3}$$

Kf = thermal conductivity of fibers = 84 W/m-K

Km = thermal conductivity of matrix = 6.23 W/m-K

$$K = (.6)(84) + (.4)(6.23) = 53 \text{ W/m-K}$$

Coefficient of thermal expansion

$$C = \frac{VfCfEf + VmCmEm}{E} \qquad (1.4)$$

Cf = coefficient of thermal expansion of fibers

$= -.55 * 10^{-6}$ in/in-F

Cm $= 8 * 10^{-6}$ in/in-F

$$C = \frac{(.6)(-.55)(34) + (.4)(8)(4.5)}{(22 * 10^{6})}$$

$$C = .144 * 10^{-6} \text{ in/in-F}$$

FINGER LATCH CALCULATIONS:

The last element of the drill string will experience the severest loading of the finger latch joints. This load will be

$$F = ma \tag{2.1}$$
$$F = (415\ kg)(1.63\ m/s^2) = 676.5\ N$$

The cross sectional area a latch is

$$A = wd$$
$$A = (.003\ m)(.03\ m) = 9.0 \times 10^{-5}\ m^2 \tag{2.2}$$

Thus the stress on one latch is,

$$\sigma = F/A = (676.5\ N/4)\ /9.0 \times 10^{-5}\ m^2$$
$$\sigma = 1.87\ MPa$$

For Stainless Steel σ_y = 964.6 MPa
(S30100 Full Hard)

In the event one latch carries the entire tensile load,

$$\sigma = 676.5\ N\ /\ 9.0 \times 10^{-5} m^2$$
$$\sigma = 7.51\ MPa$$

Even under these circumstances, the latches still have a large factor of safety. Failure by yielding is extremely remote.

HEAT PIPE CALCULATIONS:

BACKGROUND

Design Parameters:

Liquid Mercury / Steel Container Heat Pipe
Steel Wick

Length, $L = 1.75$ m
Evaporator Section Length, $L_e = 0.50$ m
Condensor Section Length, $L_v = 0.50$ m
Outer Diameter, $d_o = 0.0127$ m
Vapor Core Diameter, $d_v = 0.0122$ m
Estimated Operating Temperature $T = 500\ ^\circ K$

A typical estimate for the maximum power transfer of a heat pipe is,

$$q = \frac{2\ A_w g\ H_e \rho_l^{3/2} \left(\frac{\rho_v \rho_l}{\mu_l \mu_v}\right)^{1/2} l_m K_1}{L} \qquad (3.1)$$

where,
A_w = wick area
g = gravitational acceleration
H_e = heat of vaporization for the working fluid
ρ_l = liquid density
ρ_v = vapor density
μ_l = liquid viscosity
μ_v = vapor viscosity
l_m = wicking height of fluid
K_1 = wick factor
L = heat pipe length

Since of the above properties vary considerably with temperature, the calculations for the heat pipe are based on an estimated axial heat flux for a typical mercury steel heat pipe:

$$q'' = 25.1\ W / cm^2 \text{ at } T = 533^\circ K$$

CALCULATION OF HEAT TRANSFER LIMITATIONS:

The majority of the following information was taken from Log Property versus Log Temperature tables. As a result, the accuracy of the values and calculations are limited.

Data for Heat Transfer Limitation Calculations: ($T = 500^\circ K$)

Vapor core diameter, $d_v = 0.0122$ m
Vapor density at stagnation pressure, $\rho_o = 4.2 \times 10^{-3}$ kg / m^3
Heat of Vaporization, $\lambda = 348.6 \times 10^3$ J / kg
Molecular weight, M = 200.59 kg / kg mole

Vapor density, $= 1$ kg/m^3
Specific heat ratio, $\gamma_v = 1.67$
Surface Tension $\sigma =$ ~~N / m~~ .4231 N/m
Wick surface pore hydraulic radius, $r_{h,s} = 0.000445$ m
Evaporator Section Length, $L_e = 0.75$ m
Thermal Conductivity of Container, $k_w = 17.3$ W / m°K
Thermal Conductivity of Fluid, $k_l = 12.975$ W / m°K
Nucleation radius, $r_n = 2.54 \times 10^{-4}$ m
Universal Gas Constant, $R_u = 8.314 \times 10^3$ J / kg mol K

Sonic Limit
$$Q_{s,max} = A_v \rho_o \lambda \left[\frac{\rho_o R\ T}{2(\gamma_v + 1)}\right]^{1/2} \quad (1.2)$$

$$A_v = \frac{\pi(0.0122)^2}{4}$$

$$R = \frac{8.314 \times 10}{200.59}$$

$$Q_{s,max} = (1.169 \times 10^{-4})(4.2 \times 10^{-2})(348.6 \times 10^3) \left[\frac{(1)(41.48)(500)}{2(1.67 + 1)}\right]^{1/2}$$

$$Q_{s,max} = 10.66 \text{ W}$$

Entrainment Limit
$$Q_{e_{max}} = A_v \lambda \left(\frac{\rho_v \sigma}{2\ r_{h,s}}\right)^{1/2} \quad (1.3)$$

$$Q_{e_{max}} = (1.169 \times 10^{-4})(348.6 \times 10^3)\left(\frac{(.4231)(1)}{2(0.000455)}\right)^{1/2}$$

$$Q_{e_{max}} = 889.02 \text{ W}$$

Boiling Limit
$$Q_{b_{max}} \cong \frac{2\pi L_e k_e T}{\lambda \rho \ln(r_i / r_v)}\left(\frac{2\sigma}{r_n}\right)$$

$$k_e = \frac{k_l\ k_w}{k_l + k_w} = \frac{(17.30)(12.975)}{17.30 + 12.975} = 7.4143 \text{ W / m°K} \quad (1.4)$$

$$Q_{b_{max}} = \frac{2(3.1416)(7.4143)(500)}{(348.6 \times 10^3)(1)(\ln\ .1512)} \quad \frac{(2)(.4231)}{(2.54 \times 10^{-4})}$$

$$Q_{b_{max}} = 1472 \text{ W}$$

In summary,

$$Q_{s_{max}} = 10.66 \text{ W}$$

$$Q_{e_{max}} = 889 \text{ W}$$

$$Q_{b_{max}} = 1472 \text{ W}$$

Theorectically, (based on typical values for mercury / steel heat pipes)

$$Q_{max} = Aq''$$

$$Q_{max} = (25.1)(1.27)$$

$$Q_{max} = 31.877 \text{ W}$$

Thus, the limitation calculations were correct to an order of magnitude and the maximum heat transfer for a single heat pipe is approximately 11 watts.

With 12 heat pipes embedded in the drill bit, the heat pipes will remove 12 x 11 Watts or 132 Watts.

SOLENOID CALCULATIONS

Mass Values(kg)	Force Values(N)	Current Values(amps)
0.25	35	2.397518
0.5	70	4.795037
0.75	105	7.192556
1	140	9.590075
1.25	175	11.98759
1.5	210	14.38511
1.75	245	16.78263
2	280	19.18015

Velocity = 14 m/s   Area = 0.0036   C = 10.3

Delta T = 0.1 s   n = 100

Force = F = m(dv/dt)   l = 0.254

Current = I = (F*l)/(C*A*n)   (4.1)

where: C = pull per amp turn (from chart)

A = area of solenoid plunger

l = length of solenoid in meters

n = turns of coil

F = desired force

POWER SUPPLY CALCULATIONS

The following calculations were based on information obtained from vendor catalogs pertaining to the products of Eagle-Picher Industries, Inc. These battery cells already have applications in both the military and space programs. The silver zinc secondary cells, product number SZLR 320, were the package from which the calculations were extrapolated.

	Amp hours	# of cells	lbs
SZLR 320	320	120	723

	length(in)	width(in)	height(in)	vol(cubic cm)
SZLR 320	26.4	8.5	7.0	134,000

This package will provide 320 amp hours per cell. In order to determine just the ampheres the amp hours must be divided by a factor of ten since this type of battery is rechargable.

$$\text{Current} = \frac{320 \text{ amp hours}}{10} = 32 \text{ amps}$$

The battery package is capable of 1.55 working voltage.

Power = (32 amps)(1.55 volts)(120 cells)

Power = 6.00 kw

APPENDIX C

PROGRESS REPORTS

DEVELOPMENT OF A LUNAR DRILLING IMPLEMENT

Progress Report 1/15/87

At present the most promising drilling rig under consideration is shown in the accompaning figure. Drilling rods held in a carousel on the platform are guided through the drill chuck. The drill chuck is used to facilitate easy handling of the drill string.

Several drilling operations are being considered at this time.

Rotation - This method would likely require a large amount of thrust and axial load to break rock with large compressive strengths.

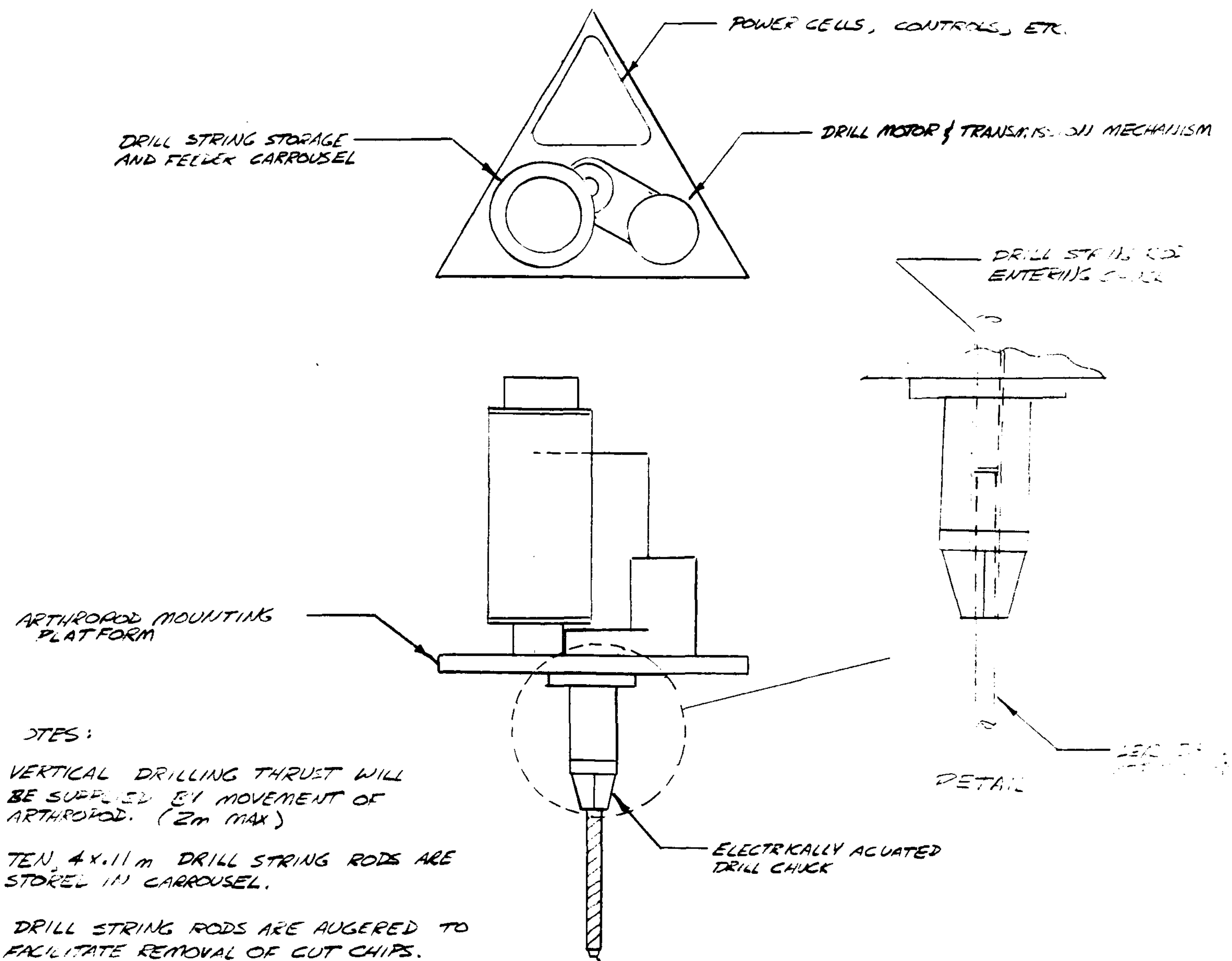
Percussion - Due to the drilling depth a down-the-hole type drill will need to be developed. Position of the bit will have to be controlled.

Rotary-Percussive - Percussive action to break rock and rotation to shear peaks and remove cuttings.

Propellant Firing - Shoot pellets from drill to break up the rock and use rotation to remove cuttings.

Rotating Saw - By rotating saw the rock may be cut or planed away.

Rotation of a screw type drill string is being considered as a means of removing cuttings during dry drilling.



OTES:

1. VERTICAL DRILLING THRUST WILL BE SUPPLIED BY MOVEMENT OF ARTHROPOD. (2m MAX)
2. TEN, 4 x .11 m DRILL STRING RODS ARE STORED IN CARROUSEL.
3. DRILL STRING RODS ARE AUGERED TO FACILITATE REMOVAL OF CUT CHIPS.
4. IN ADDITION TO HOLDING DRILL STRING DURING ROTARY DRILLING OPERATION, THE DRILL CHUCK WILL INCREASE THE EASE OF ATTACHING DRILL STRING RODS TOGETHER.
5. DRILL BIT WILL CONTAIN AN INTERNAL COOLING MANIFOLD.

INITIAL CONCEPT FOR A LUNAR DRILLING IMPLEMENT

T.S.

PROGRESS REPORT

27 JAN 87

TO: J. W. Brazell

FROM: Group II

SUBJECT: Lunar Drilling Implement

During the past week the following changes have been made with regard to the Lunar Drilling Implement design:

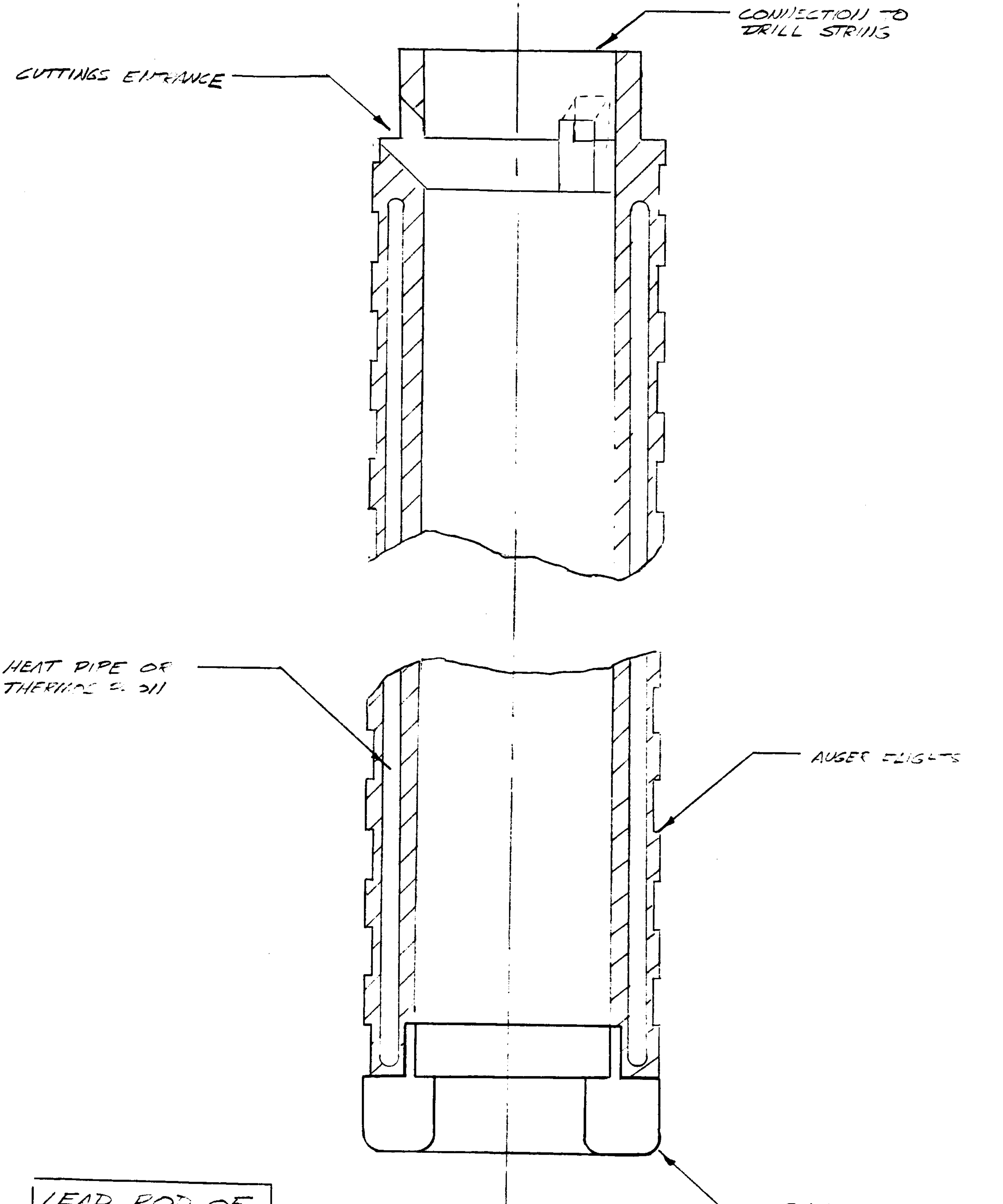
Two new concepts have been devised for removing the cuttings from the drilled hole. An auger will still lift the chips away from the cutter head, but after a 1 meter rise they will be channeled to the inside of the hollow drill string. At this point the chips will be removed either by hoisting a collection basket or ejected them via a "flinger".

A robot arm has been added to facilitate the assembly and disassembly of the drill string and the changing of the cutter heads.

The drill string components and the spare cutter heads will be carried in free standing trays or will be attached to the arthropod's legs.

The cutter head will be cooled by means of a heat pipe

As more information concerning the characteristics of lunar soil is gathered, a suitable cutter head can be selected and drilling parameters can be established. This will in turn determine power consumption and thus fuel cell requirements. Investigation continues into materials suitable for the lunar environment.



LEAD ROD OF
DRILL STRING

LUNAR DRILLING IMPLEMENT

PROGRESS REPORT 2/5/87

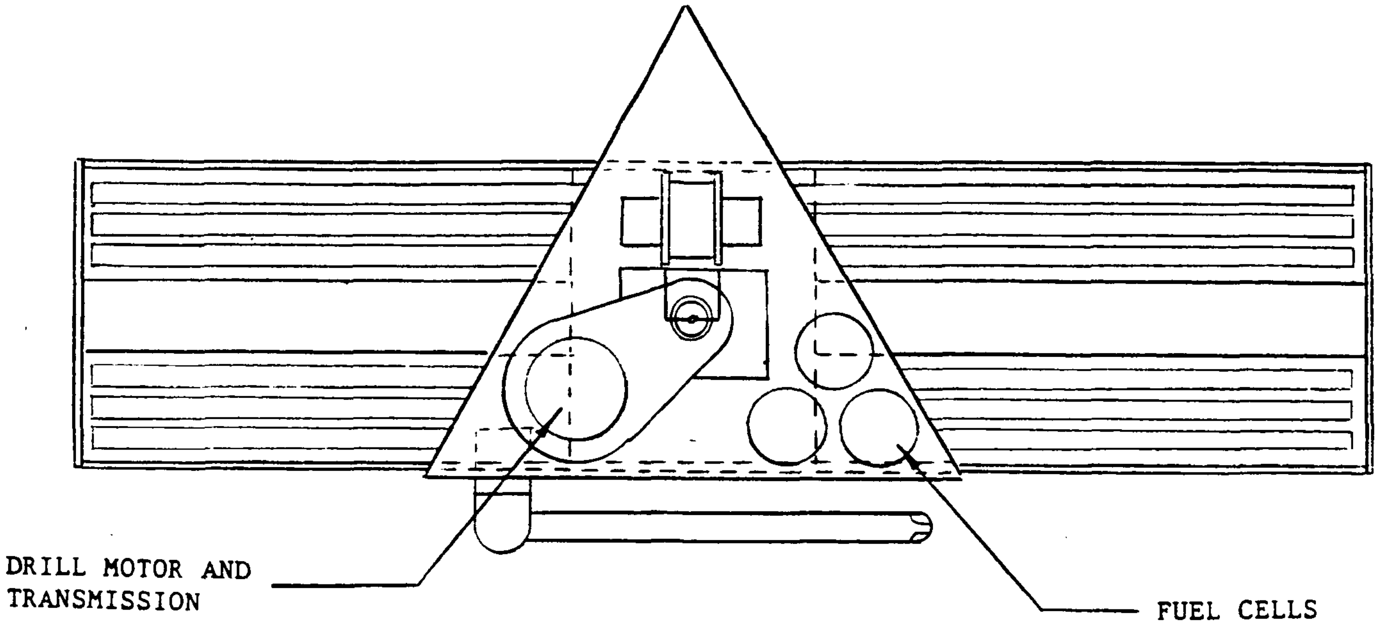
TO: MR. BRAZELL
FROM: GROUP 2

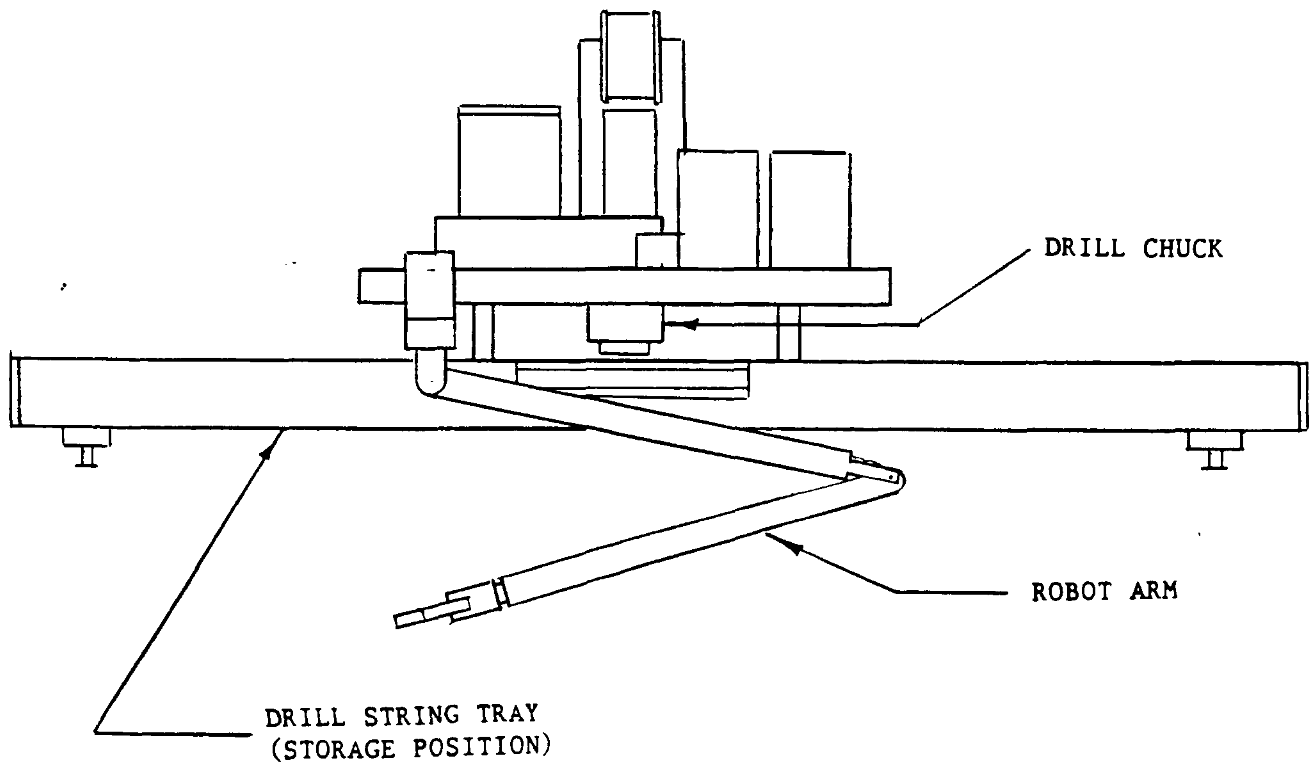
DURING THE PAST WEEK A MORE IN DEPTH STUDY WAS MADE INTO THE TYPES OF MATERIALS SUITABLE FOR USE ON THE MOON. TO OPTIMIZE THE WEIGHT OF OUR EQUIPMENT AND TO AVOID COLD WELDING OF METALS, COMPOSITE MATERIALS WERE INVESTIGATED. POLYIMIDE TYPE COMPOSITE MATERIALS HAVE MUCH HIGHER WORKING TEMPERATURES THEN CONVENTIONAL EPOXY RESIN MATERIALS AND CAN BE MANUFACTURED WITHOUT VOIDS OR POROSITY. GRAPHITE FIBERS WERE CONSIDERED FOR THEIR HIGH STRENGTH AND LOW THERMAL EXPANSION COEFFICIENTS WHICH IS IMPORTANT FOR THE WIDE RANGE OF TEMPERATURES ON THE MOON. TO PROTECT THE GRAPHITE/POLYIMIDE DRILL STRING FROM RADIATION DAMAGE EITHER A THIN FOIL CAN BE PUT ON THE OUTSIDE OF THE RODS OR THEY CAN BE PAINTED. THE INSIDE PLIES OF THE DRILL ROD LAMINATES CAN BE MADE USING KEVLAR FIBERS DUE TO THEIR HIGH IMPACT RESISTANCE.

THROUGH INVESTIGATION OF PAST RESEARCH EFFORTS IT WAS DETERMINED THAT A DRILL BIT MADE FROM CUBIC DIAMOND WITH A FACE NORMAL TO THE CUTTING SURFACE SIGNIFICANTLY INCREASES BIT LIFE.

WORK ON SOIL MECHANICS HAS SHOWN THAT THERE ARE FOUR TYPES OF LUNAR SOIL INCREASING IN HARDNESS WITH INCREASING DEPTH. IT WAS DETERMINED THAT IT WILL BE NECCESSARY TO CASE THE HOLE DURING THE FIRST SEVERAL METERS TO PREVENT COLLAPSE OF THE SHAFT.

POSSIBLE WAYS OF REMOVING THE CHIP BASKET FROM THE DRILLED SHAFT ARE STILL BEING INVESTIGATED. SEVERAL METHODS ARE THE USE OF A WENCH, SPRING WITH A STOPPER, AND AN EXPLOSIVE CARTRIDGE.





LUNAR DRILL
GROUP

PROGRESS REPORT

LUNAR DRILLING IMPLEMENT

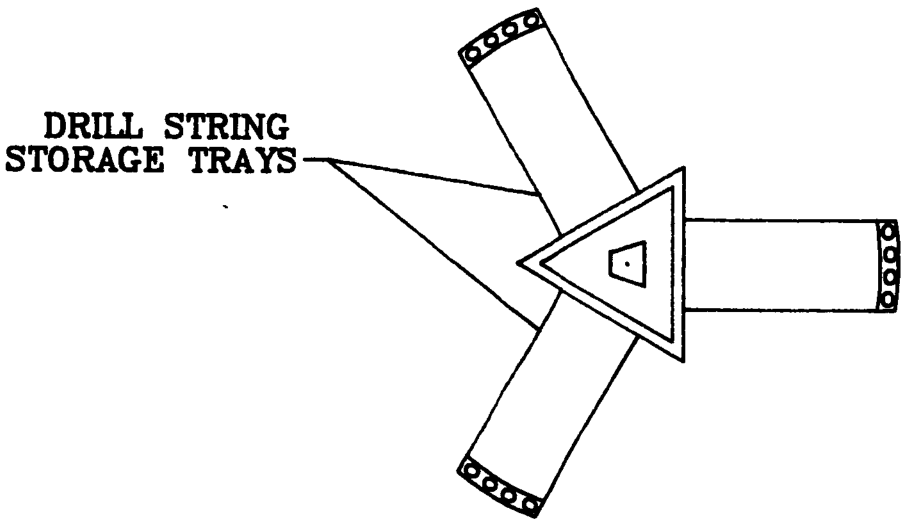
DATED: 2/12/87

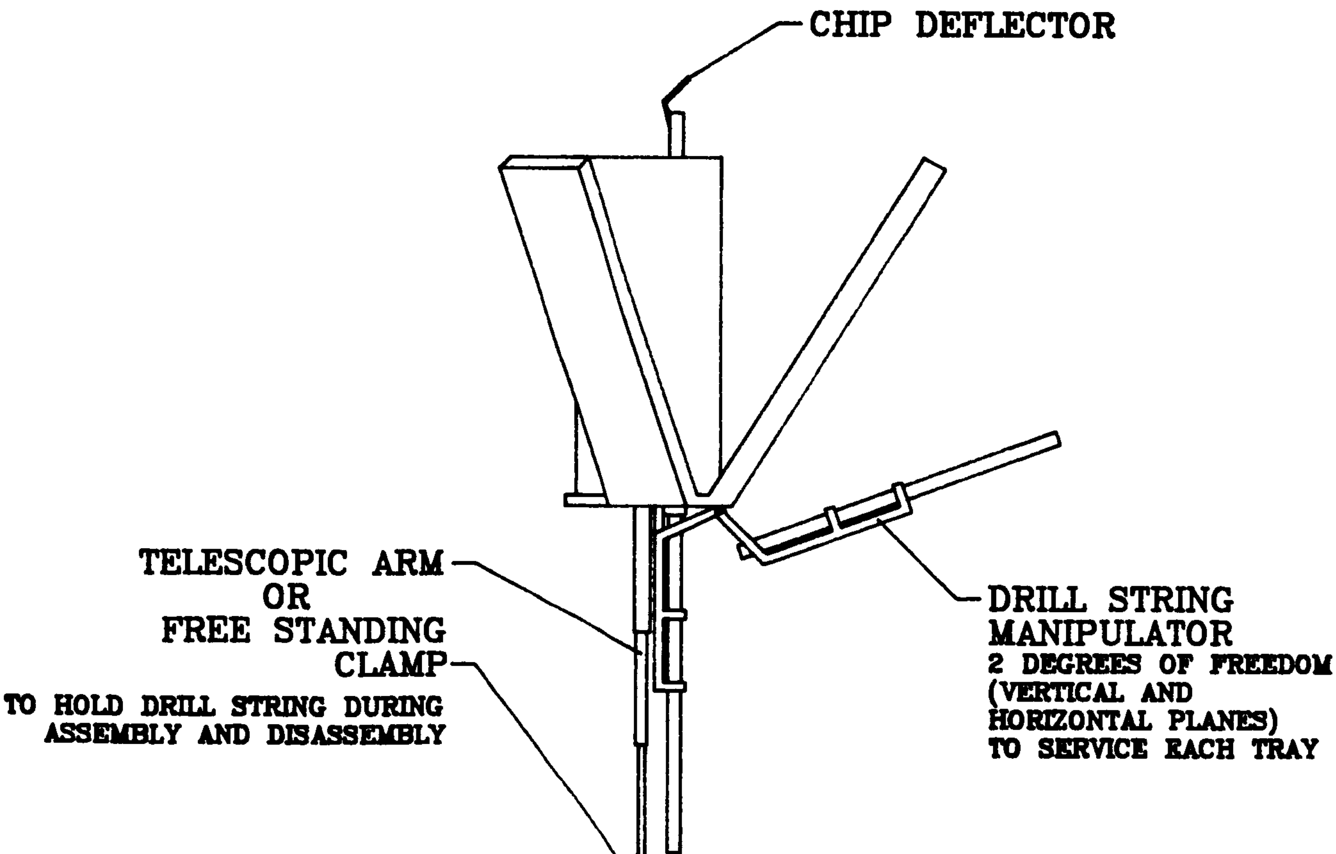
TO: MR. BRAZELL
FROM: GROUP 2

DURING THE PAST WEEK RESEARCH HAS BEEN CONDUCTED IN THE AREAS OF POWER SUPPLY, DRILL ROD CONNECTIONS, AND MOTORS. THE TYPES OF POWER SOURCES INVESTIGATED WERE SILVER-ZINC SECONDARY CELLS AND SEALED NICKEL-CADMIUM CELLS AND BATTERIES, BOTH MANUFACTURED BY EAGLE-PICHER INDUSTRIES. THE SILVER ZINC CELLS ARE OF TWO TYPES ONE WITH A CYCLE LIFE PERIOD OF 4-6 MONTHS THE OTHER 18 MONTHS. BOTH REQUIRE 12 HOURS FOR RECHARGING. EACH [illegible] WEIGHS 7.9 OUNCES, HAS A VOLUME OF 7.4 CUBIC INCHES AND A POWER OUTPUT OF 12 AMP HOURS. THE TEMPERATURE RANGE OF THE SILVER-ZINC CELLS IS 40 F TO 165 F. ANOTHER TYPE OF FUEL CELL WITH A TEMPERATURE RANGE FROM -65 F TO 200 F IS LISTED AS CLASSIFIED MATERIAL. THE INVESTIGATION INTO VARIOUS MOTORS IS ALSO BEING DONE THROUGH VENDOR CATALOGS. DR. DAVEY WILL BE CONTACTED FOR HIS ADVICE WHEN HE RETURNS FROM OUT OF TOWN ON MONDAY. RESEARCH OF A METHOD FOR CONNECTING THE RODS WITHOUT INVOLVING SCREW THREADS IS BEING CONDUCTED THROUGH PATENTS AND VENDOR CATALOGS.

SEVERAL DECISIONS HAVE BEEN MADE AS TO THE CHIP REMOVAL PROCESS AND THE DRILL STRING ASSEMBLY. FOR CHIP REMOVAL A PLUNGER OPERATED BY EITHER A LATCHED SPRING OR A SOLENOID WILL SHOOT THE CHIP BASKET UP THE INSIDE OF THE DRILL STRING. A METHOD FOR STORING AND ASSEMBLING THE DRILL STRING HAS BEEN DECIDED UPON. THE RODS WILL BE STORED ON THE LOWER SIDE PANELS OF THE ARTHROPOD AND A ROTATING ARM WILL BRING ONE ROD DOWN AT A TIME AND LOAD IT INTO THE CHUCK. A COLLAR ON THE END OF A COLLAPSABLE ROD WILL HOLD THE DRILL STRING IN PLACE AT THE ENTRANCE TO THE HOLE.

LUNAR DRILLING IMPLEMENT





PROGRESS REPORT

LUNAR DRILLING IMPLEMENT

To: Mr. Brazell

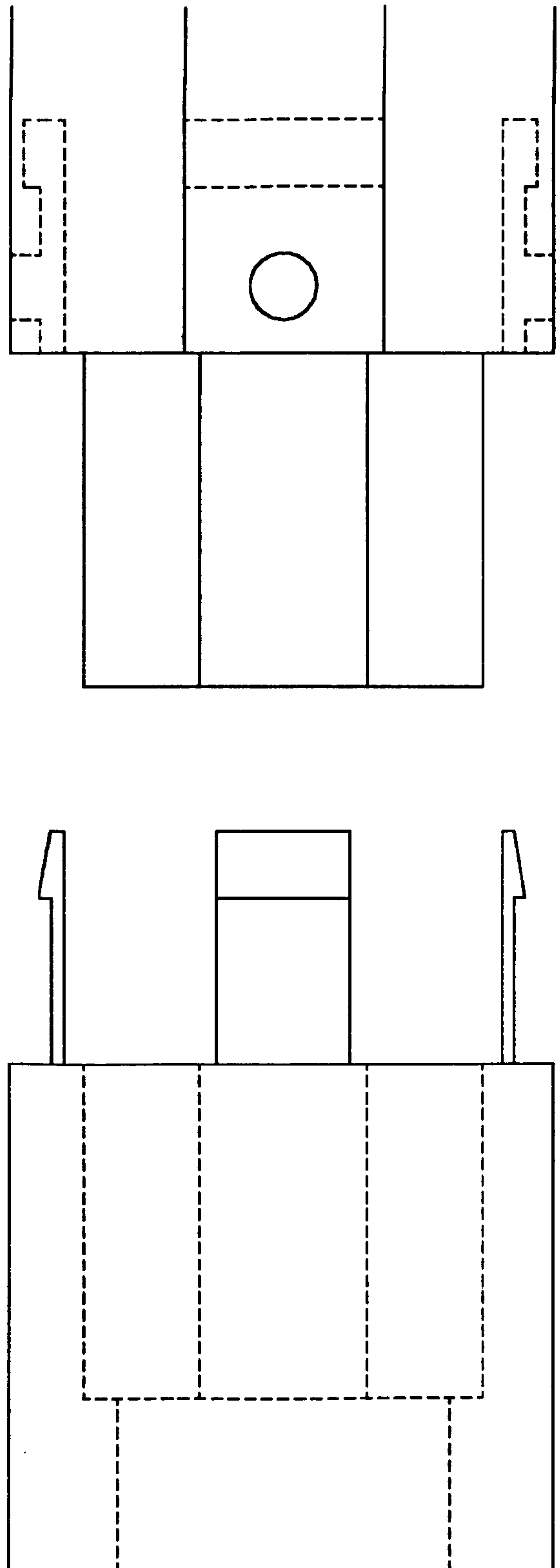
From: Group II

Date: February 19, 1987

During the past week, the following ideas have been studied in our group: new drill string, joint design proposals, type of drilling diamond, heat pipe vendors, various motors, and a computer program to locate the manipulator arm layout and pivot point.

We have decided on a GEO SET drilling diamond by General Electric Specialty Materials for the drilling bit. The fact that the diamond is self sharpening is advantageous because most diamonds polish rather than sharpen with wear. This is relatively new technology that surpasses our previous plans for the bit. Along with the drill bit operation, various heat pipe vendors are being investigated. These companies include Hughes Aircraft - Electron Dynamics Division and Astrodyne Incorporated.

Dr. Davey was reached for comment on the motor. After talking to him the following conclusion was made: a curvelinear sinchronous motor will be used which will need 12 to 15 sets of plates for entire motor approximately 34 inches in diameter. The operating temperature of the motor is to be figured soon.



COMPOSITE

DRILL STRING

CONNECTION

LUNAR DRILLING IMPLEMENT

Progress Report
26 FEB 87

The following progress has been made in the outlined areas:

<u>Drill String</u> : connection design modified
: candidate materials evaluated
: cost, weight, and stress parameters analyzed

<u>Drill Bit</u> : designed

<u>Solenoid</u> : governing equations and recommendations provided by Calvin Miller (Bell Labs)
: vendor catalogs consulted

<u>Power Supply</u> : use of batteries recommended by Karl Faymon (Lewis Research Center)
: vendor catalogs consulted

<u>Motor</u> : Dr. Davey is out of town

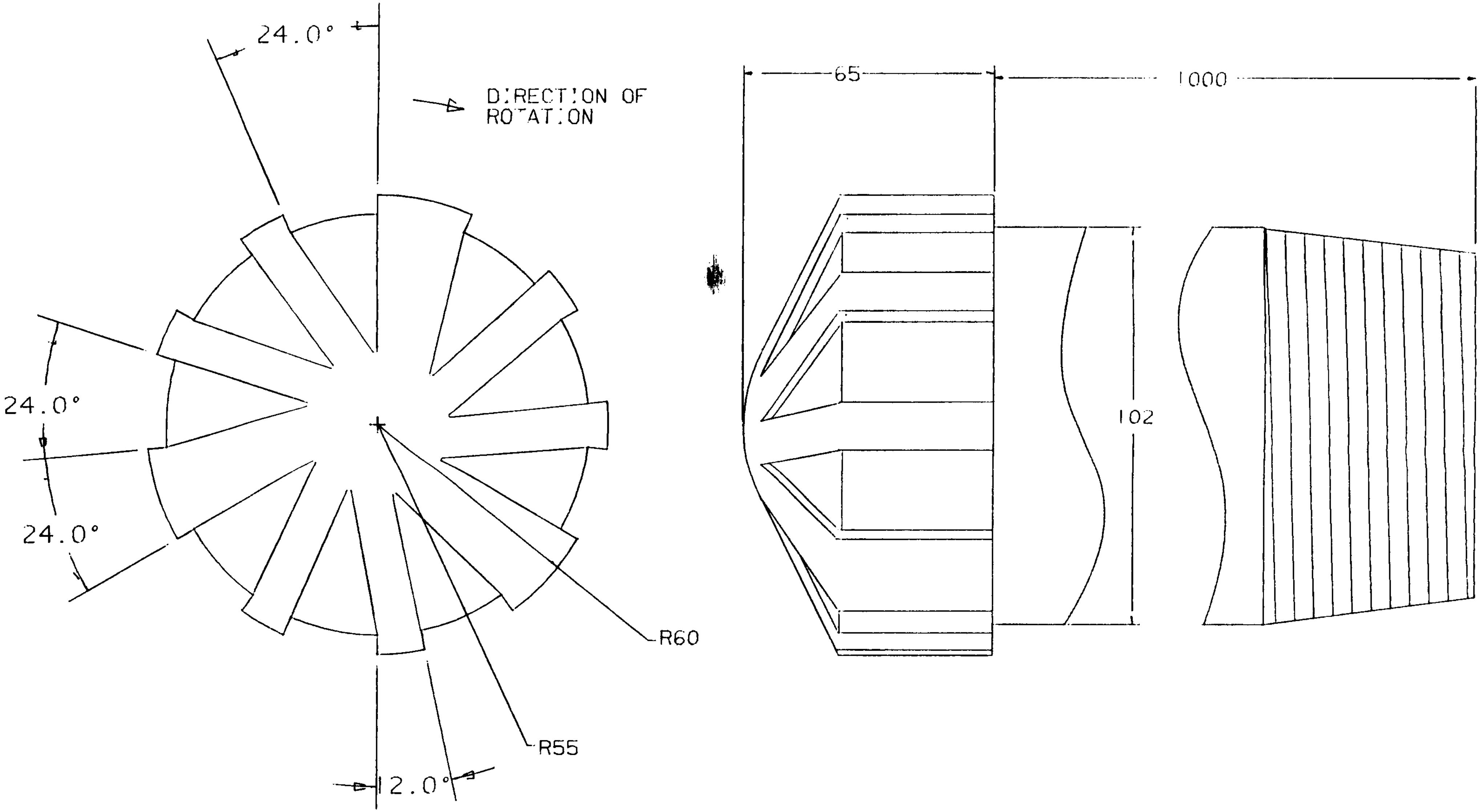
<u>Heat Pipes</u> : meeting with Dr. Coldwell scheduled

<u>Manipulator Arm</u> : design refinement underway

<u>Research</u> : search initiated by Martha Griffin

Writing of the report sections dealing with each of the above areas continues.

Overall design dimensions are in the process of being determined so that construction of the model can begin.



NOTE CUTTING DIAMONDS OMITTED FOR CLARITY

TITLE DRILL BIT	
LUNAR DRILLING IMPLEMENT	
DATE 2/24/87	DWG NO.